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Prediction of the abrasion resistance of construction steels on the basis of the subsurface deformation layer in a multi-pass dual-indenter scratch test

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ABSTRACT

Multi-pass dual-indenter (MPDI) scratch tests were carried out on a wide range of steels with different microstructures to investigate the relation between the formation of subsurface deformation layers under repetitive local sliding contact and their abrasion resistance. Five steel grades with different work hardening capability, i.e. Interstitial-Free steel, Fully Martensitic steel, Dual Phase steel, Quench Partitioning steel and TWining Induced Plasticity steel were selected. The results of this well-defined local contact damage test method and those of the standard ASTM G65 dry sand rubber wheel abrasion test were correlated. Results suggest that the abrasion resistance of steels is controlled by the properties of the work hardening layer formed beneath the abraded surface and depends on the thickness of the work hardening layer. When applying the correct evaluation parameters the new scratch test MPDI methodology reproduces the material response to the ASTM G65 abrasion test rather well and provides a reproducible and quantitative method to screen the abrasion resistance of new construction steels. Moreover, the MPDI test allows to quantitatively evaluate the abrasion resistance of steels for working conditions beyond those of the standardized G65 test.

1. Introduction

Abrasive wear is one of the predominant wear processes encountered in steel components used in automotive, transportation, mining, agricultural and earth moving industries [1,2]. It is a complex process involving not only the complexity of the tribosystem and the prevailing working/testing conditions [1,3,4], but also the dynamic development of a (sub) surface microstructure due to the plastic deformation of materials during the abrasion process [5–10]. The evolving microstructure of a material at and below the worn surface differs from the initial microstructure because of plastic deformation and local work hardening. During the steady state of the actual abrasion process, it is the work hardened (sub) surface layer that undergoes the abrasive wear [11,12]. This evolution of local mechanical properties and changes in the damage mechanisms in the zone exposed to abrasive attack is seen as one of the principal obstacles to build a general and quantitative model for the abrasion rate as a function of mechanical properties of the as-exposed material [4].

Usually experiments to study the abrasive wear behaviour of materials are done with a two-body abrasive wear test set-up, such as the pin-on-disc wear test, the paddle wear test, a polished sample against abrasive paper, etc., [2,3,13–15] or a three-body abrasive wear test set-up, such as sand/rubber wheel abrasion tester, i.e. materials worn against abrasives [16–20]. Although such experiments provide useful data on the relative wear rate of materials under practical conditions, they give virtually no information on the actual deformation and damage processes. Hence the outcome of such tests does not allow predicting the wear resistance of new (not-yet-tested) materials or new working conditions [21]. In order to study and predict the abrasive wear characteristics of materials under different load conditions relevant to the real work environment, a novel multi-pass dual-indenter (MPDI) scratch test approach has recently been developed, in which scratch tests with a small pointed indenter are performed on a pre-scratched surface produced by a large indenter via multi-pass sliding at various load levels [22].

The aim of the present work is to use the MPDI scratch test approach to investigate the abrasive wear behaviour upon sliding

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point contact and to establish a relation between the thickness and characteristics of the work hardening layer formed and the resulting failure mechanism. Of special interests are a comparison of the MPDI scratch test results with those of the ASTM G65 abrasive wear test and the exploration of the notion that the MPDI test may provide insight into the abrasion resistance for working conditions beyond the G65 standard (load and particle size) conditions. Five steel grades with different work hardening capability, i.e. Interstitial-Free steel (IF steel), Fully Martensitic steel (FM steel), Dual Phase steel (DP steel), Quench and Partitioning steel (Q&P steel) and TWining Induced Plasticity steel (TWIP steel) were selected.

2. Experimental description

2.1. Materials and specimen preparation

Five steel grades with different work hardening capability, i.e. Interstitial-Free ferritic steel (IF steel), Fully Martensitic steel (FM steel), Dual Phase steel (DP steel), Quench and Partitioning steel (Q&P steel) and TWining Induced Plasticity steel (TWIP steel) were selected for this study. The chemical compositions (in wt%) of the steels are listed in Table 1. All steels are in the metallurgical state to be expected for their grades. More detailed descriptions of the microstructures of these five steels can be found in [22]. Prior to experimental testing, ASTM G65 test samples were mechanically grinded. All samples for MPDI scratch test were mounted in cold-setting resin and mechanically polished following a standard metallographic preparation process.

2.2. Hardness tests

The micro-hardness measurements were carried out using a Vickers indenter under a load of 200 g. The results are given as average values of 10 separate measurements for each material. The hardness values are listed in Table 1. The hardness of the IF steel was the lowest due to the soft nature of the single phase ferrite, while the FM steel possessed the highest hardness because of the hard martensite. The DP and Q&P steels, which consist of mixtures of ferrite/martensite and martensite/retained austenite, respectively, showed intermediate levels of hardness. The TWIP steel, initially having a fully austenitic matrix, displayed the second lowest hardness.

2.3. Multi-pass dual-indenter (MPDI) scratch tests

The multi-pass dual-indenter (MPDI) scratch tests were performed with a CSM micro-scratch tester. 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°. The sliding speed in the tests was 30 mm/min. All sliding were made perpendicular to the rolling direction. A fixed scratch length of 5 mm was produced with the large indenter, and a 4 mm scratch was superimposed by the small indenter along the axis of the big pre-scratch track. All tests were conducted at room temperature under a relative humidity ranging from 40% to 80%. A typical MPDI scratch test consists of three steps:

1. Multi-pass (typically 10 passes) pre-scratching of the original surface with the large indenter, employing vertical loads ranging from 1 N to 30 N in order to create a well-defined deformation hardened layer of variable thickness.
2. Pre-scanning of the profile of the central region of the scratch track formed using the small indenter and a very low load of 0.03 N such as not to cause any further damage or deformation.
3. Scratching finally at the bottom of the scratch track created by the large indenter with multiple passes using the small indenter and a fixed vertical load of 0.3 N in order to induce local damage in the surface hardened layer, in a manner comparable to that encountered during the steady state of the multi-body abrasion testing.

All sliding tracks made with the small indenter were in the very centre of the scratch tracks made by the large indenter. The scratch depths to be reported refer to the penetration depth by the small indenter scratching only. 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 0.3 N. The penetration depth is derived from the difference of the two steps. Based on the preliminary methodological study reported elsewhere [22], 10 sliding passes with the large indenter were made in the pre-scratching stage so as to prepare a well-defined and representative deformed surface in a steady state.

2.4. ASTM G65 test

In order to benchmark the MPDI scratch responses, a standardized low stress abrasion test was performed on all five materials exactly following the ASTM G65 dry sand rubber wheel abrasion (procedure B). Samples along the rolling direction were prepared and the surface was polished following a standard metallography method. The ASTM G65 test was performed with wheel rotations of total 2000 at a speed of 200 rpm and standard Ottawa silica sand as the abrasive medium. After the test, the weight loss of the sample was measured with a precision of 1 mg. The test for each material in the current investigation was repeated 3 times, and an average weight loss is reported.

2.5. Metallography and observation of the worn surfaces

After the scratch test and the ASTM G65 abrasive wear test, a scanning electron microscope (SEM) operating at 5 kV was employed to observe the worn surface. After this inspection stage, cross-sections of the wear track perpendicular to the sliding direction were prepared to observe the microstructure development under the worn surface using SEM. After the scratch test on the ASTM G65 worn surface, the surface topography of each steel was characterized by the Confocal Laser Scanning Microscopy (CLSM).

Table 1
Chemical compositions, microstructures and micro-hardness of the steel grades examined.

Material	Chemical composition (in wt%)	Microstructures	Hardness $Hv_{0.2}$ [kg/mm^2]
IF steel	0.0009C–0.1Mn–0.11Ti–0.02Cr	Ferrite	100 ± 3
FM steel	0.15C–1.9Mn–0.2Si–0.15Cr	Martensite	482 ± 9
DP steel	0.15C–1.9Mn–0.2Si–0.15Cr	Ferrite + martensite	316 ± 8
Q&P steel	0.22C–1.8Mn–1.4Si	Ferrite + martensite + retained austenite	308 ± 6
TWIP steel	0.60C–18.0Mn–1.5Al	Austenite (twin)	241 ± 2