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Correlating the abrasion resistance of low alloy steels to the standard mechanical properties: A statistical analysis over a larger data set

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ABSTRACT

In the literature many researchers have tried to correlate the (dry) abrasion resistance of steels to their standard mechanical properties as determined in simple tensile and hardness testing. However, many unclear or even conflicting correlations have been reported, in part due to small data sets being used, different testing methods and relatively simple data processing techniques. In the present work 40 different low alloy steels were tested using the same ASTM G65 abrasion test and standard mechanical testing. The data set consists of 20 samples having the same chemical composition yet processed to different microstructures and different mechanical properties, as well as 20 steel grades with various compositions but having mechanical properties comparable to the first data set. The results show that for steels of the same composition significantly higher correlations between the abrasion resistance and certain mechanical properties (in particular strength coefficient *K*, hardness and UTS) are observed than those for steels having different compositions. In case both data sets were combined and a new regression analysis was applied, the quality of the correlation dropped significantly and the correlations became barely statistically relevant. Furthermore, when taking into account the measurement errors in both independent and dependent variables, the correlation coefficient became even worse and no statistically relevant correlation was observed at all. The current study clearly casts doubts on the validity of reported correlations between material (mechanical) properties and abrasion resistance.

1. Introduction

Abrasive wear is one of the dominant wear processes encountered in steel components used in the earth moving, mining and mineral processing, and agricultural industries [1,2]. Wear loss is the result of a complex tribo-system response depending not only on the materials in contact but also on the working/testing conditions applied. Hence, the (dry) abrasion resistance is not an intrinsic material property to be determined unambiguously and dedicated experiments are required to determine its actual value for the practical condition envisaged. However, from a material development perspective it would be very desirable if the abrasion resistance could be estimated on the basis of well-defined material (mechanical) property parameters, such as Vickers hardness (*Hv*) [2–7], ultimate tensile strength (UTS) and yield strength (YS) [8–14], strain hardening exponent (*n*) [9,15], uniform elongation (UE) [16,17], or energy to tensile failure (ETF) [18]. As abrasive wear in steels necessarily involves local plastic deformation/strain hardening, one would expect a simple relationship between the abrasion resistance and the hardness of a material as proposed by Rabinowicz [3] for single phase metallic systems. However, many investigations have demonstrated that the straightforward correlation does not hold true and even '*V*' and '*S*' shaped correlations between the hardness and the abrasion resistance have been reported [19–22]. In particular for advanced multi-phase low alloyed steels strongly non-linear correlations between the abrasion resistance and the hardness as well as other tensile properties have been observed [8,9,12,15,23]. The reported contradictory dependences of the abrasion resistance against basic material (mechanical) properties can be due to various causes such as limited data sets, an imperfect separation of micro-structural and compositional effects, an overly simplified statistical analysis, the use of different testing methods or to the absence of a unique correlation.

The aim of the present work is to use a single industry accepted (dry-) abrasion test (ASTM G65), conventional tensile and hardness testing and a larger data set of 40

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industrially produced low alloy steel grades, as well as professional linear regression methods to determine whether such correlations between the abrasion resistance and standard mechanical properties of low alloyed construction steels for abrasive applications may exist. With the application of the statistical methods, it will be possible to examine whether (linear and single parameter) correlations proposed in the literature on the basis of results for a modest number of samples are generally valid when tested over a wider range of carefully selected samples of controlled composition and microstructures. The total data set in the analysis consists of 40 steels of which 20 belong to a steel of fixed composition (22MnB5) heat treated to different microstructures and 20 belong to commercial low alloy steels of various chemical compositions but with comparable mechanical properties to the first data set. Seven independent mechanical properties were used in the correlation studies. Four different linear regression methods were employed.

2. Experimental procedure

2.1. Materials and sample preparations

The 40 steels tested belong to two different data sets:

- Group A consists of 20 grades all made from a single hot rolled 22MnB5 steel with a fixed chemical composition (Fe–0.22C–1.2Mn–0.25Si–0.2Cr in wt%) yet processed to distinctly different microstructures and mechanical properties.
- Group B consists of 20 commercial low-alloyed steels of various chemical compositions and microstructures but with mechanical properties comparable to those of group A.

For the samples belonging to group A, a hot rolled 22MnB5 steel of 3 mm thickness was firstly homogenised at 1200 °C for 24 h in a hydrogen atmosphere followed by air cooling. After homogenisation, the steel was heat treated according to four different heat treatment routes to generate different microstructures and properties: (a) full Austenisation, then Intercritical annealing to form ferrite necklace structures followed by Quenching (AIQ); (b) Intercritical annealing, directly from the Ferrite/pearlite starting microstructure followed by Quenching (FIQ); (c) Intercritical annealing from an almost fully Martensitic starting state followed by Quenching (MIQ); and (d) full Austenisation, then a Quenching and Tempering (Q&T) treatment followed by quenching to produce tempered martensitic (TM) microstructures. The detailed heat treatment routes and resulting microstructural configurations can be found elsewhere [15,23,24]. Group B consists of 20 commercial low alloyed commercial construction steels with different chemical compositions and/or different microstructures, i.e., Ferritic, Martensitic, DP (Dual Phase), TRIP (Transformation Induced Plasticity) and FH (Full Hard) microstructures. The TRIP steels had a triple-phase microstructure consisting of ferrite, bainite/martensite and retained austenite. The FH material had a ferritic-pearlitic microstructure which was obtained in the intermediate state after cold rolling but before annealing.

2.2. Mechanical properties measurement

The mechanical properties of all steel grades were measured using two different techniques: tensile testing and micro-hardness testing. The hardness measurements were carried out using a Vickers indenter under 2 N load and the average value for 10 measurements is reported. The tensile test was executed for each grade using A25 specimens having a gauge length of 25 mm. The strain rate was $10^{-3}\,s^{-1}$. The longitudinal sample direction was taken parallel to the rolling direction. The tensile test was executed only twice given the good reproducibility of the properties of these commercially processed steel grades. From the hardness and tensile test measurements the following parameters were determined: the hardness *Hv*, the yield stress YS, the ultimate tensile stress UTS, the uniform elongation UE, the energy to fracture ETF and the strength coefficient *K* and the strain hardening exponent *n* in the Hollomon equation (i.e., $\sigma = K \cdot \ln\varepsilon$). In the present work the value of *K* is derived from the intercept of linear fitting of the plastic part of curve $\ln\sigma$ v.s. $\ln\varepsilon$ while the value of *n* is equal to its slope, as described in [15]. The strength coefficient *K* is equal to the stress where the strain is equal to 1 (or $\ln\varepsilon = 0$), which represents the strength of materials to resist the plastic deformation. In line with the analysis in reference [15], the *K* and *n* employed here to correlate the abrasion resistance (weight loss) correspond to the low load condition, considering the fact that the ASTM G65 test represents a low-stress three body test.

2.3. ASTM G65 abrasion testing

The standard ASTM G65 dry sand rubber wheel abrasion test was performed on all samples using exactly the same testing conditions with a total of 2000 rotations at a speed of 200 rpm following the procedure B. The sand used as the abrasive medium is supplied by US ‘Ottawa silica’ as specified in the ASTM G65 standard and following AFS 50/70 specification. The rubber wheel is fabricated by the BRADKEN company according to the ASTM standard. Samples were taken such that the rolling direction coincided with the direction of the abrasion testing. Prior to abrasion testing the surface of each sample was polished following a standard metallography method. All tests were conducted at room temperature under a (uncontrolled) relative humidity ranging from 40% to 80%. Before and after the test, the sample weight was measured to 1 mg after careful cleaning and removal of unattached abrading particles. For each steel grade the abrasion resistance (i.e. the weight loss) was determined using three separate samples.

3. Regression and Errors-in-Variables (EIV) modelling

Regression analysis is a statistical method that estimates the statistical relevance between a dependent and one or more independent variables. The experimental data observed are obtained from different measurement techniques having different specific standards and uncertainties. Hence, the data set consists of variables that are subject to measurement error of unequal variance and are composed of varying numbers of measurements. This greatly complicates the correlational analysis between the variables. The classical approach is to assume a linear dependence between the (measurement error free) independent parameter and the (measurement error containing) dependent parameter. The least-squares approximation $\hat{X}_{ls}$ as a solution to optimise the problem is given by [25]:

$$\left\{\hat{X}_{ls}, \Delta B\right\} := \arg \min_{X,\Delta B} \|\Delta B\|_F \tag{3.1}$$

$$\text{subject to } AX = B + \Delta B \tag{3.2}$$

The unique solution $\hat{X}_{ls} = (A^T A)^{-1} A^T B$ is defined as the least-squares solution. Although arguably reliable under certain