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Examination and comparison of various erosive wear models

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Abstract

A number of erosive wear models have been developed over the years. This paper examines some of the simpler ones that are defined more clearly in terms of easily measurable mechanical properties. In some cases, such models have yet to be fully explored, especially with regard to their applicability to more commercially important materials. The predictions of the chosen models were explored using a set of heat-treated steels. It was found that for erosion at normal incidence a model by Hutchings [I.M. Hutchings, Wear 70 (1981) 269–281], gave good agreement with experimental results. The model considers that an elementary volume of deformation produced by a single particle impact is removed when a critical strain is reached. The present work showed that uniform tensile strain is proportional to this critical strain. A further model developed by Hutchings [I.M. Hutchings Tribology: Friction and Wear of Engineering Materials, Edward Arnold, London, UK, 1992] for erosion at oblique angles was also explored. This indicated a dependence of erosion on hardness. A reasonable agreement with experimental results was found if it was assumed that the wear coefficient *K* was also a function of hardness. Other models explored gave poorer agreement with experimental data. The shortcomings of all the models were considered. It is suggested that microstructural factors often play a strong role, in addition to their influence on mechanical properties.

Keywords: Erosion models; Heat-treated steels; Mechanical properties; Critical strain

1. Introduction

Erosive wear is undoubtedly a difficult process to examine and understand. It involves a stress system of a complex nature, large plastic deformations and high strain rates. The severity of the erosion process may also lead to significant microstructural changes in the surface layer. Mixing of the original microstructural constituents and incorporation of erodent fragments into the surface material are both possible. It is not surprising therefore that there is no universally accepted predictive model. However, a number of erosion wear models have been proposed in the past literature. The more rigorously derived ones offer little possibility for experimental validation. In these models, the theoretically derived predictions of erosion rate encompass a large number of parameters, both mechanical and physical properties, often experimentally difficult to determine under the conditions pertaining to erosion.

Simpler models have also been developed. These models tend to indicate the primary importance of one or two mechanical properties. However, there is again the problem of how to define and measure these properties under the strains and strain rates typical of erosion. The near impossibility of this has meant that most workers have used properties measured under more conventional conditions. Despite the relative simplicity of these models, their validity and agreement with experiment has often been insufficiently explored, even by the authors themselves. What work has been done is inconclusive. In many cases there is a need to examine the models more fully, both for a wider range of materials and for ones with greater engineering importance. Models by Hutchings [1,2] and Sundararajan [3] were chosen for examination in this work. The mechanical properties of a wide range of steels were measured along with their erosion rates, and these were compared with the predictions of the models. By doing so it was intended to assess the accuracy and predictive capability of each of the models, understand their shortcomings and the reasons why, and suggest refinements to improve them.

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2. Experimental details and results

Steels were chosen for the test programme because of their commercial importance and their ability to be heat-treated into a variety of conditions with a wide range of mechanical properties. Two steels were selected; a eutectoid 0.8% C steel (EN42) and a 0.4% C low alloy steel (EN24). The nine heat-treated conditions and resultant hardness values are summarised in Table 1. Note the codes given to each of the heat-treated materials. These codes will be referred to subsequently. Table 1 indicates that the materials may generally be paired in terms of equal Rockwell hardness values. However, the yield stress and UTS of the paired materials may differ (Table 3) depending on their work hardening behaviour. Work hardening will in turn depend on microstructural characteristics.

Each of the heat-treated materials consisted essentially of carbides (Fe_3C), of various sizes and shapes, in a ferrite matrix of varying toughness. The pearlitic steels (42P and 24P) had carbide lamellae typical of such materials. The lamellae of 24P were finer (∼0.4 μm thickness) than those of 42P (∼1 μm), owing to the greater alloy content of EN24 and the lower transformation temperature of the heat treatment process. Upper bainite (UB) also contained plate-like carbides of similar thickness to the 24P pearlite lamellae. However, the ferrite in UB is relatively harder and more brittle owing to the presence of dislocations resulting from the bainitic transformation. Hence, UB has higher yield strength and UTS than 24P (see Table 3). Spherodised pearlite contained carbides that were generally spherical in shape, and up to 2 μm in diameter, embedded in a soft ductile ferrite matrix. The steels M450, M550, M650 and M700 had relatively fine carbides typical of tempered martensite. LB was similar in microstructure to M450. As expected the carbide size increased with tempering temperature, having a maximum diameter of around 0.5 μm after a 700 °C temper. Tempering also affected the toughness of the ferrite matrix. The ferrite of M450, M550 and LB was generally brittle in nature owing to the presence of a significant dislocation density resulting from quenching. In contrast, the ferrite of M650 and M700 was much tougher, these steels gaining their strength from the fine ferrite grain size.

The erosion tester selected for the test programme was a rotating disc accelerator erosion tester. The tester allows a range of impact angles between 5° and 90° and velocities up to 35 m s^{-1}. For each steel, a matrix of test conditions

Table 1
The heat treatments used to produce the desired microstructures for the test programme

Steel	Microstructure	Code	Rockwell C scale hardness	Heat treatment process
EN42	Pearlite	42P	16	850 °C/1 h, rapidly cooled to 690 °C, isothermally transformed at 690 °C, air cooled
EN42	Spherodised	42S	16	850 °C/1 h, rapidly cooled to 570 °C, isothermally transformed at 570 °C, air cooled tempered at 700 °C/24 h, air cooled
EN24	Pearlite	24P	25	850 °C/1 h, rapidly cooled to 620 °C, isothermally transformed at 620 °C, air cooled
EN24	Upper bainite	UB	35	850 °C/1 h, rapidly cooled to 400 °C, isothermally transformed at 400 °C, air cooled
EN24	Lower bainite	LB	45	850 °C/1 h, rapidly cooled to 320 °C, isothermally transformed at 320 °C, air cooled
EN24	450 °C tempered martensite	M450	45	850 °C/1 h, oil quenched, tempered at 450 °C/0.5 h, air cooled
EN24	550 °C tempered martensite	M550	40	850 °C/1 h, oil quenched, tempered at 550 °C/0.5 h, air cooled
EN24	650 °C tempered martensite	M650	35	850 °C/1 h, oil quenched, tempered at 650 °C/0.5 h, air cooled
EN24	700 °C tempered martensite	M700	24	850 °C/1 h, oil quenched, tempered at 700 °C/0.5 h, air cooled

Table 2
Steady state erosion rates for different test conditions

Steel	Steady state erosion rates (mm^3 kg^{-1})								
	15 m s^{-1} impact			25 m s^{-1} impact			35 m s^{-1} impact		
	8°	30°	90°	8°	30°	90°	8°	30°	90°
42P	3.234	1.535	0.335	5.377	3.603	2.048	13.508	8.335	5.029
42S	1.759	0.924	0.426	4.877	3.389	1.899	22.012	11.056	5.283
24P	1.447	0.400	0.307	2.428	2.322	1.425	6.284	7.596	5.235
UB	2.138	1.293	0.335	4.291	3.812	2.785	12.124	7.143	4.320
LB	3.234	1.400	0.649	19.059	9.549	4.008	20.082	12.046	7.531
M450	2.919	1.942	0.914	11.142	7.311	3.940	20.891	13.072	8.318
M550	4.277	2.153	0.607	15.994	6.732	4.125	30.354	22.883	11.923
M650	1.251	1.100	0.467	6.826	6.121	2.707	10.767	10.497	4.514
M700	1.481	1.242	0.698	8.719	4.943	2.261	40.058	22.613	10.483