

The Erosion-Corrosion Performance of SA213-T22 Steel in Low Velocity Conditions

J.G. Chacón-Nava, F.H. Stott, A. Martínez-Villafaña, F.M. Almeraya-Calderón, and J.G. González-Rodríguez

(Submitted 5 April 2001; in revised form 17 May 2001)

The erosion-corrosion (E-C) behavior of SA213-T22 steel has been studied in a laboratory fluidized-bed (FB) facility in the temperature range from 100 to 600 °C. Tests were carried out on pin specimens in air using alumina particles of 560 μm average size at impact velocities from 1.5 to 4.5 m/s. The trends of wear with temperature showed small weight gains at velocities up to 1.5 m/s. Erodent deposition was a dominant process at temperatures below about 300 °C and velocities below about 2 m/s. At higher velocities, a peak wastage temperature was observed at about 350 °C. The wastage/temperature curves observed in both cases suggested four temperature regions. In each region, a different E-C regime operates. Scanning electron microscopy (SEM) revealed various wastage mechanisms, *i.e.*, (a) oxide chipping, (b) development of a compact and adherent oxide scale, (c) oxide and metal removal, and (d) fracture and spalling within the oxide layer and at the scale/metal interface. In the present study, the latter mechanism was responsible for the high wastage rates observed at temperatures above about 450 °C and impact velocities above 3.5 m/s.

Keywords erosion-corrosion, laboratory test, low-alloy steel, low-impact velocity, temperature effects, wastage mechanisms

1. Introduction

The erosion-corrosion (E-C) of materials at high temperatures has received much attention in recent years due to the occurrence of the degradation phenomenon in a broad range of industries. For instance, due to the increasing demand in power generation and environmental issues, the utilization of technologies related to combustion of coal in fluidized beds (FB) presents important advantages over conventional pulverized coal boilers. Some of them are as follows: (a) excellent heat transfer; (b) good combustion efficiencies; (c) low emission of contaminants, *i.e.*, SO_x and NO_x ; and (d) good fuel flexibility, accepting virtually any fuel. In spite of their advantages, these units can suffer materials degradation due to E-C. Components, such as in-bed heat exchangers, are impacted by high concentrations of particles moving at low velocities, *i.e.*, ≤ 5 m/s.^[1]

Erosion-corrosion is a degradation process resulting from the interaction of both erosion and corrosion in a synergistic manner, *i.e.*, aided by each other. The complexity of E-C is indicated by the fact that the effects of some variables in each component are not fully understood in many cases. Nevertheless, several scenarios have been proposed to classify the E-C of materials into “regimes.”^[2–5] These regimes have been subdivided according to various criteria, which differ for the

various investigators. Thus, differences should be expected, although, in general, the regimes are commonly related to temperature. Regarding these E-C regimes, a few mechanisms have been proposed on the basis of experimental results obtained at low-impact velocities. Sethi and Wright^[6] proposed that each erosion impact removes a footprint of scale by brittle fracture, up to a critical thickness beyond the scale does not behave in a brittle manner, and it is assumed that all the particle energy is contained in the oxide layer. These authors suggested three broad regimes as follows: regime 1, where the oxidation rate is low due to a low temperature; regime 2, where wastage is dominated by erosion-assisted scale exfoliation; and regime 3, where the oxidation rate is rapid compared with the rate of oxide thinning by erosion. Stack *et al.*^[7] proposed four regimes: (a) erosion-dominated (corrosion is negligible); (b) E-C dominated (corrosion enhances erosion); (c) corrosion-dominated 1 (corrosion inhibits erosion); and (d) corrosion-dominated 2 (erosion is negligible). Since materials degradation due to E-C has been a continuing problem in industrial processes, such as combustion of coal in FB, attempts have been made to understand the factors controlling the E-C phenomena including field testing^[1,8] and laboratory testing.^[9,10,11]

The purpose of the present work was to investigate the E-C behavior of SA213-T22 steel, which is widely used as material for heat exchangers in FB systems. The influence of test temperature and particle-impact velocity on the transitions between the different E-C regimes and wastage mechanisms is discussed.

2. Experimental Method

The E-C experiments were performed in an FB rig, which has been described in detail elsewhere.^[12] Basically, this consists of light FB of particles in which cylindrical specimens are rotated in the vertical plane into and out of the bed. Depending upon the angular velocity chosen, the linear velocity of the specimens relative to the particles is achieved. The conditions used were

J.G. Chacón-Nava, A. Martínez-Villafaña, and F.M. Almeraya-Calderón, Centro de Investigación en Materiales Avanzados S.C., División de Deterioro de Materiales e Integridad Estructural, 31109 Chihuahua, Chih., México; F.H. Stott, Corrosion and Protection Centre, UMIST, Manchester, M60 1QD, United Kingdom; and J.G. González-Rodríguez, Universidad Autónoma del Estado de Morelos, Cuernavaca, Morelos, México. Contact e-mail: jchacon@cimav.edu.mx.

the following: temperatures of 100, 250, 300, 400, 450, 500, 550, and 600 °C; an exposure time of 24 h; air as oxidizing gas; impact velocities from 1 to 4.5 m/s; and angular alumina particles of 560 μm average size. Owing to degradation, the particles were replaced at regular intervals. The material tested was SA213-T22 steel of nominal composition 2.25Cr-1Mo. For all the specimens, their surfaces were ground with 800 grit paper and degreased with acetone before the experiments were commenced. Weight-loss measurements, coupled with scanning electron microscopy (SEM) with respect to the area of the specimen that impacted the particles, were taken to indicate the main trends of the effects of temperature and impact velocity and to characterize the extent of degradation of the specimens. X-ray diffraction (XRD) was used as a complementary technique.

3. Results

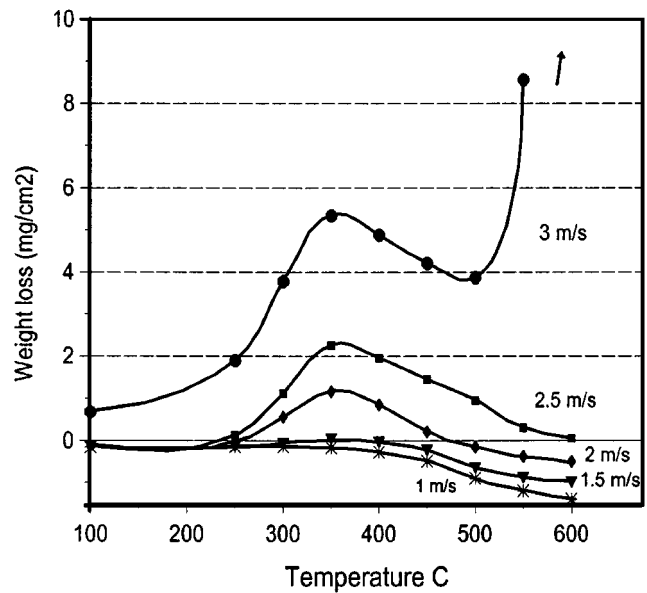
Figure 1 shows the behavior of the T22 steel as a function of temperature and specimen velocity. At impact velocities up to 1.5 m/s, small weight gains were recorded. However, in the velocity range from 2 to 3 m/s, a wastage peak at about 350 °C was clearly noted. At temperatures higher than 350 °C, the weight loss fell sharply, becoming practically zero at 600 °C. From 3 to 4 m/s, the weight loss increased rapidly with temperatures up to 350 °C. Further increases in temperature to about 500 °C caused very little change in weight loss, giving the appearance of a “plateau” zone. At higher temperatures, the wastage increased significantly, although this was less marked at 3 m/s. At the highest velocity, a similar trend was observed, but, here, the end of the plateau zone occurred at about 450 °C.

At the lowest temperatures and velocities, the eroded surfaces consisted mainly of compacted erodent (and erodent debris). X-ray mapping shows this (Fig. 2a and b). Ripple formation was observed at all temperatures at velocities below 3 m/s. For instance, Fig. 3(a) shows ripples at 450 °C and 2.5 m/s. Here, energy dispersive x-ray (EDX) analysis on the surface revealed iron and oxygen peaks, but no chromium peak was detected (Fig. 3b). Results from XRD showed that the oxide formed was Fe_2O_3 (Table 1). Examination of a cross section showed a discontinuous and not fully developed oxide scale (Fig. 4). However, at 600 °C, an adherent and compact scale was observed (Fig. 5a). Under these conditions, EDX analysis mainly detected iron and oxygen, but now a small chromium peak was also seen (Fig. 5b). Results from XRD showed that Fe_2O_3 was the main oxide formed, but FeCr_2O_4 was also detected (Table 2). Further increase in velocity to 4.5 m/s resulted in spallation and development of cracks through the scale. Plan and cross-sectional micrographs gave evidence of this, as seen in Fig. 6(a) and (b).

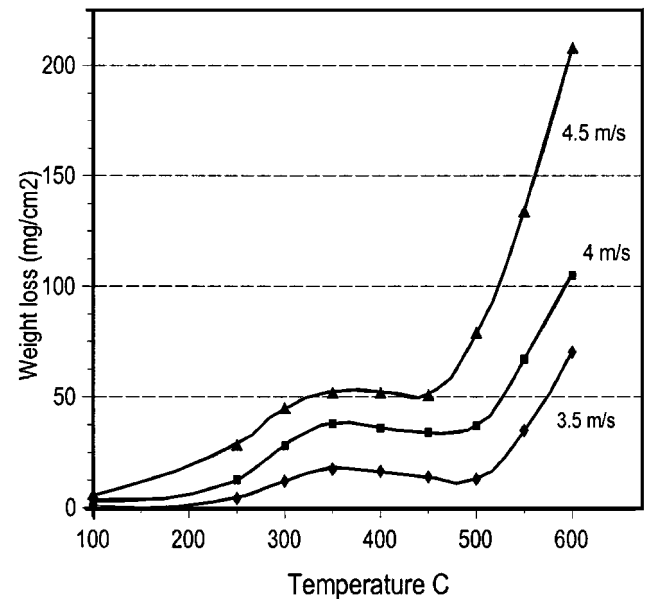
4. Discussion

4.1 Wastage Trends

The wastage trends with temperature and impact velocity suggest four temperature regions as follows.



(a)



(b)

Fig. 1 Weight change as a function of temperature and specimen velocity for the T22 steel exposed in the FB rig with 560 μm alumina particles for 24 h

Region I, observed at temperatures below 200 °C. Here, in general, weight gains or small weight losses are recorded. In the former case, these weight gains were associated with erodent deposition, as was confirmed by SEM analysis.

Region II, observed from 250 to 350 °C in the velocity range from 2 to 4 m/s. Here, a significant increase in wastage is noted. Since the mechanical properties that may have an effect on erosion (such as hardness and ductility) change very little below 350 °C,^[13] they cannot totally account for the observed changes in rates of wastage. On the other hand,

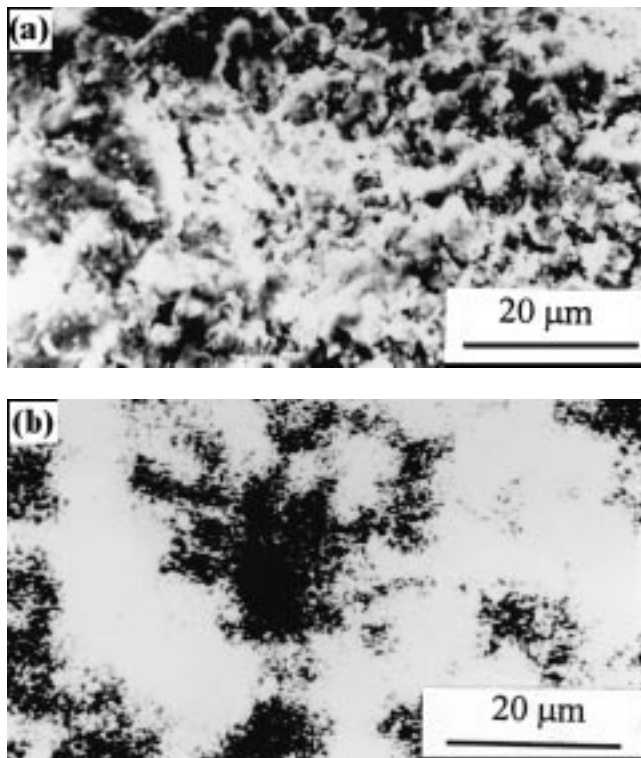


Fig. 2 Scanning electron micrographs of the T22 steel exposed in the FB rig at 250 °C and 1.5 m/s, with the 560 μm alumina particles for 24 h showing (a) morphology of the eroded surface and (b) x-ray map of aluminum of (a) indicating a large amount of compacted erodent on the surface

oxidation plays an important role in the extent of damage. Observations of the eroded surfaces after exposure at about 300 °C indicated that an oxide scale of about 1 μm was formed, being thicker than the one we would expect under static oxidation conditions only. A likely explanation for this is that the oxidation rate of the alloy is enhanced by erosion impacts through continuous damage and regrowth of oxide. To confirm this point, activation energies obtained from E-C data in the present work gave a value of about 28 kJ/mol (Fig. 7). Sethi and Corey^[14] reported an activation energy of about 67 kJ/mol for a 2.25Cr-1Mo alloy (similar to the T22 steel used in the present work) eroded at 2.7 m/s. Ninham *et al.*^[15] reported a value of 30 kJ/mol. These values indicate that the oxidation rate increases more rapidly with temperature than would be expected under static oxidation conditions only. In the latter case, activation energies in the range of 170 to 180 kJ/mol for low-alloy steels are typical.^[16]

Region III, observed from 350 to 600 °C. Within this region, a reduction of wastage with increasing temperature was observed. This may be associated with the formation of a compact and adherent oxide scale, which may offer better resistance against particle impingement. The oxide scale, formed during exposure at 450 °C and 2.5 m/s, provides some protection, as indicated by the weight-loss data. With further increase in temperature to 600 °C, a compact and adherent scale, about 5 μm thick, was observed, and under this condition, a minimum in weight loss was recorded. Wright *et al.*^[17]

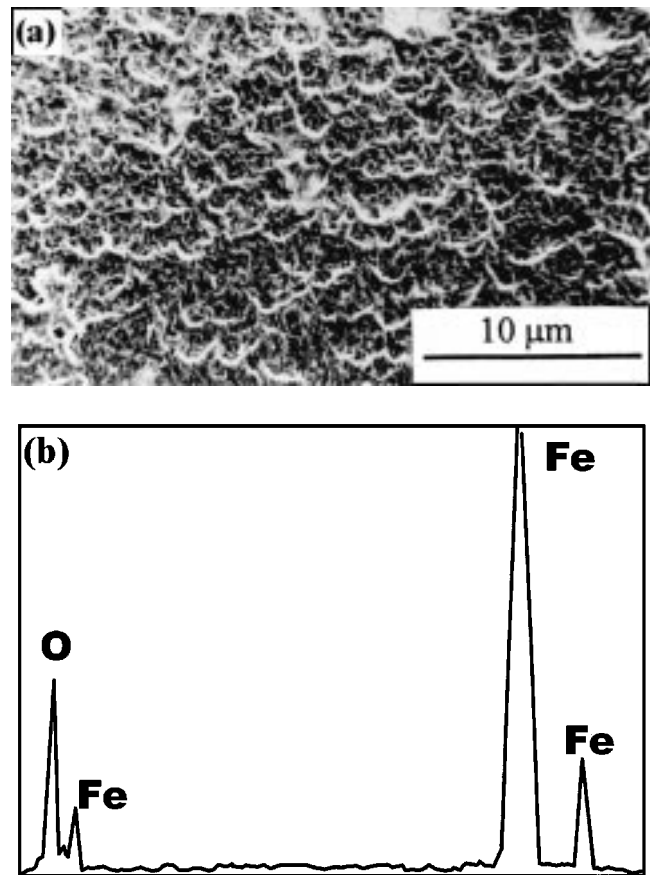


Fig. 3 Scanning electron micrograph of the T22 steel exposed in the FB rig at 450 °C and 2.5 m/s, with the 560 μm alumina particles for 24 h showing (a) morphology of the eroded surface showing ripple formation and (b) EDX analysis of surface in (a); note that no Cr peak signal was detected

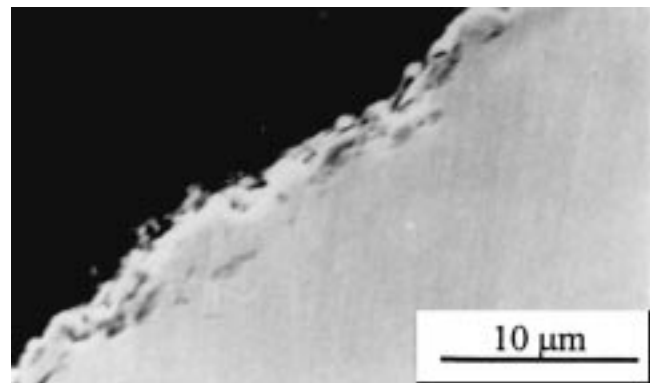


Fig. 4 Scanning electron micrograph of the T22 steel exposed in the FB rig at 450 °C and 2.5 m/s, with the 560 μm alumina particles for 24 h showing a discontinuous oxide scale in cross section

suggest that a reduction in wastage occurs for alloys that were able to develop chromia and alumina scales. However, for the steels used in the present work, these kinds of scales are not expected to form. X-ray and EDX analysis on the scales where

Table 1 The XRD results for T22 steel after exposure in the FB rig at 450 °C and 2.5 m/s, with the 560 μm alumina particles for 24 h

<i>d</i> -spacing	Relative intensity(a)	Identification
3.692	vw	Fe ₂ O ₃
2.701	m	Fe ₂ O ₃
2.643	vw	...
2.524	m/w	Fe ₂ O ₃
2.340	m/w	...
2.210	w	Fe ₂ O ₃
2.029	s	Fe substrate
1.841	w	Fe ₂ O ₃
1.695	w	Fe ₂ O ₃
1.494	w	Fe ₂ O ₃
1.487	w	Fe ₂ O ₃
1.432	m	Fe substrate
1.428	m/w	...
1.218	m	...
1.171	m	Fe substrate
1.013	w	Fe substrate

(a) s, m, and w are strong, medium, and weak intensity, respectively

Table 2 The XRD results for T22 steel after exposure in the FB rig at 600 °C and 2.5 m/s, with the 560 μm alumina particles for 24 h

<i>d</i> -spacing	Relative intensity(a)	Identification
3.670	vw	Fe ₂ O ₃
2.694	s	Fe ₂ O ₃
2.516	m	Fe ₂ O ₃
2.507	m	FeCr ₂ O ₄
2.204	m/w	...
2.024	m/w	Fe substrate
1.839	m	Fe ₂ O ₃
1.693	m/w	Fe ₂ O ₃
1.598	m/w	FeCr ₂ O ₄
1.485	m/w	Fe ₂ O ₃
1.482	m/w	FeCr ₂ O ₄
1.453	w	...
1.432	w	Fe substrate
1.170	m	Fe substrate
1.014	w	Fe substrate
0.907	w	Fe substrate

(a) s, m, and w are strong, medium, and weak intensity, respectively

the weight losses were minimal showed that the oxides formed were Fe₂O₃ and FeCr₂O₄. The present results indicate that the T22 steel exhibits a peak wastage temperature (transition from region II into region III) below about 3.5 m/s. This trend is somewhat similar (between certain temperature limits) to the observed behavior of a 2.25Cr-1Mo steel when eroded with smaller particles at velocities below 3 m/s.^[18]

Region IV, observed above 450 °C and impact velocities above 2.5 m/s. In this region, the wastage rates increased significantly with temperature and velocity. With further increases in impact velocity up to 4.5 m/s, SEM analysis showed a heavily fractured scale. Aided by temperature, fracture at the metal/scale interface and cracks within the scale occur, and these provide easier diffusion paths for oxidation.

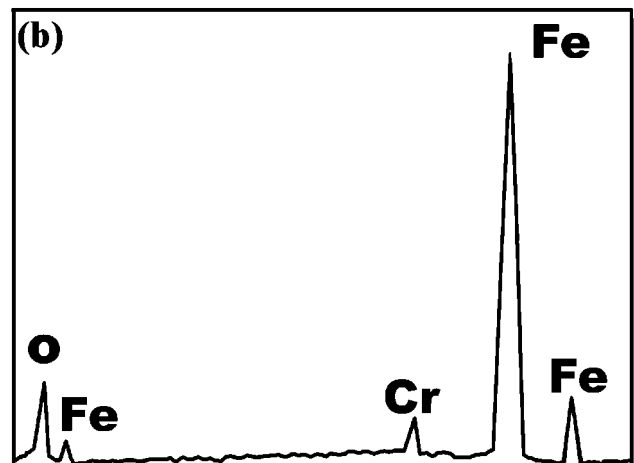
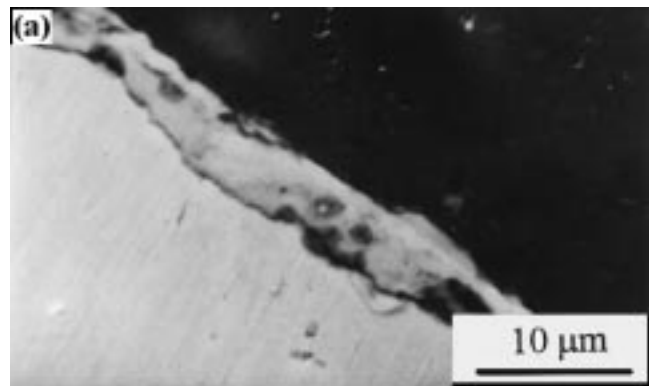


Fig. 5 Scanning electron micrograph of the T22 steel exposed in the FB rig at 600 °C and 2.5 m/s, with the 560 μm alumina particles for 24 h showing (a) the oxide scale in cross section and (b) EDX analysis of surface in (a); here, a Cr peak signal was detected

Thus, the alloy responds by an increase in the oxidation rate. This suggests that the rate of damage is controlled and enhanced by oxidation.

Mechanisms of Wastage

In the present study, the E-C mechanisms were found to be strongly dependent on the characteristics of the oxide layer formed during E-C exposure, the properties at the scale/substrate interface, and the test conditions, *i.e.*, temperature and velocity. Thus, depending on the preceding factors, different mechanisms may dominate.

At velocities below about 2 m/s and temperatures above about 500 °C, the erosion process appears to decrease the porosity level within the scale, and, importantly, it may play a role in reducing tensile stresses in the metal/scale interface. Such a situation may inhibit the development of loss of contact at the metal/scale interface. Under these conditions, the probable mechanism of wastage is one of scale chipping of small-size oxide fragments. Following exposure at temperatures up to about 350 °C, SEM examinations gave evidence of the presence of thin scales, of the order of 1 μm thick, which did not protect the substrate from damage and removal by the erosive particles. Here, the probable mechanism of wastage

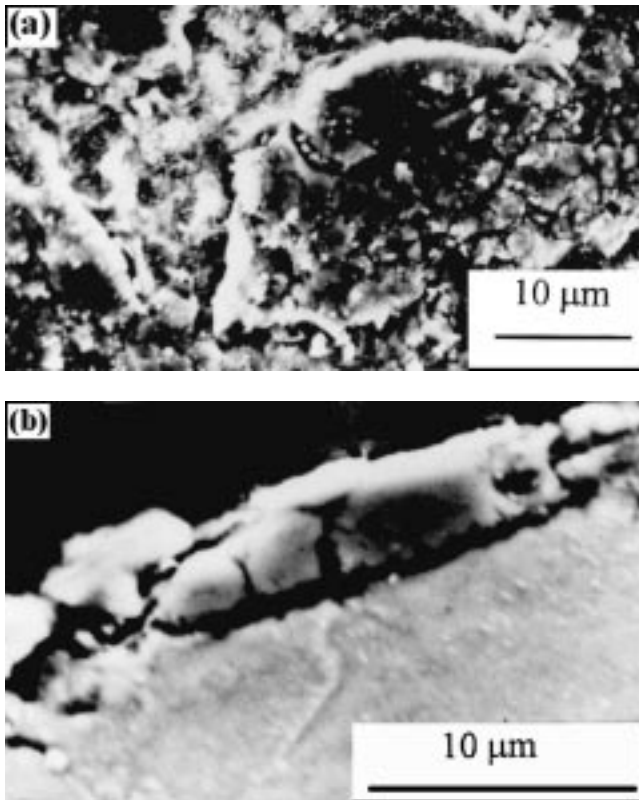


Fig. 6 Scanning electron micrographs of the T22 steel exposed in the FB rig at 600 °C and 4.5 m/s, with the 560 μm alumina particles for 24 h showing (a) plan view and (b) oxide scale in cross section

involves the removal of both oxide and base metal, with the amount of wastage increasing with increasing velocity.

The formation of an adherent and compact scale protecting the substrate against the impinging particles effectively reduces the weight losses. This behavior was observed at about 450 °C and 2.5 m/s. Figure 4 shows a discontinuous and not fully developed oxide scale that gives some protection to the substrate, as observed in the weight-loss trends under these conditions. With further increases in temperature to 600 °C and for exposures at velocities from 2 to 2.5 m/s, practically no weight losses were recorded, and under these conditions, a compact and adherent scale is observed (Fig. 5a). These observations are in sharp disagreement with the findings of Olsson *et al.*^[19] In their work with a 2.25Cr-1Mo steel (similar to the T22 steel used in the present work) at low velocities, it is found that the formation of a dense and well-adherent oxide scale did not result in any decrease in wastage rates.

At velocities above about 3.5 m/s and temperatures above about 450 °C, the crack density in the scales increased considerably (Fig. 5b). Fracture at the scale/substrate interface occurs, probably *via* large compressive stresses induced by the impact process. Buckling was not observed, but under these conditions, portions of the scale appeared to fail by wedging.

From the preceding, Fig. 8 shows schematic diagrams of the various possibilities for oxide/substrate damage observed for the SA213-T22 steel under the various conditions of temperature and impact velocity used in the present work.

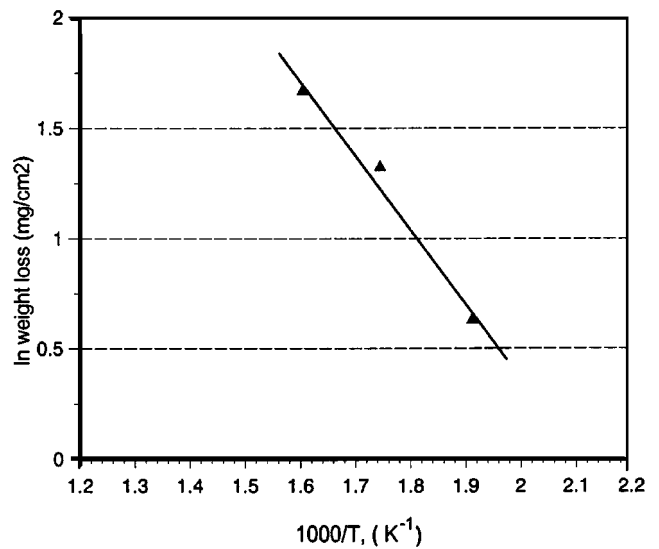


Fig. 7 Arrhenius plot of the E-C data for the T22 in the temperature range from 250 to 350 °C at 3 m/s; the activation energy derived under these conditions is 28 KJ/mol

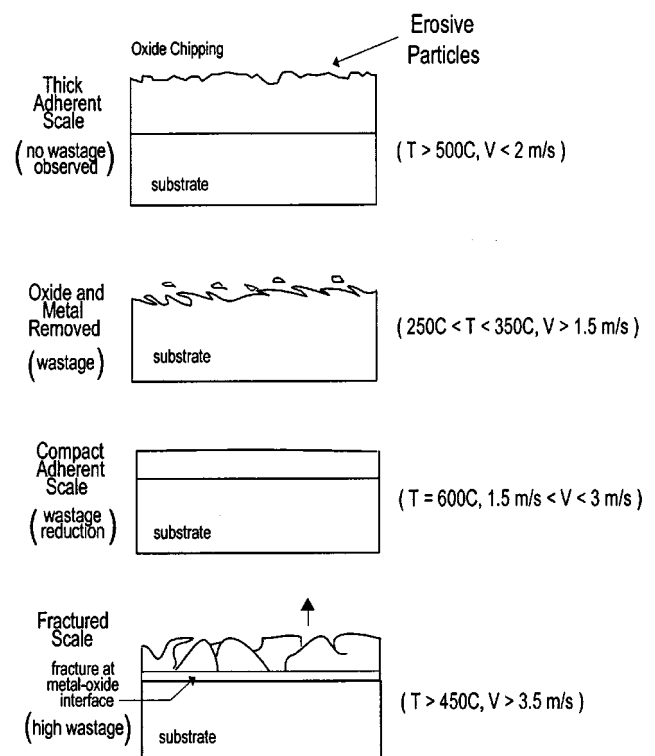


Fig. 8 Schematic diagram of the various possibilities of scale/substrate damage for the T22 steel at the E-C conditions indicated

5. Conclusions

A peak wastage temperature (PWT) was observed at about 350 °C but only within a certain velocity range, *i.e.*, 1.5 m/s < PWT < 4 m/s.

The wastage trends versus temperature suggested four temperature regions: region I, where an erosion dominated regime operates, *i.e.*, the material behavior is not dependent on oxidation; region II, where oxidation plays a significant role on the extent of damage, with the rate of erosion being enhanced by oxidation (oxidation-enhanced erosion); region III, where the main E-C regime (corrosion-dominated) is dependent on the degree of protectiveness of the oxide scale formed; and region IV, where a sharp increase in weight losses was noted, with the rate of wastage being controlled and enhanced by oxidation and the properties of the oxide scale formed. Here, an E-C dominated regime probably operated.

Erodent deposition was a dominant process at velocities below about 2 m/s and temperatures below about 300 °C. Under these conditions, small weight gains were commonly recorded.

From examinations by SEM, various wastage mechanisms could be observed: (a) oxide chipping, (b) oxide and metal removal, (c) development of a compact and adherent oxide scale, and (d) fracture and spalling within the oxide layer and at the scale/substrate interface.

Acknowledgments

Comisión Federal de Electricidad (México) kindly supplied the SA213-T22 steel used in the present research.

References

1. J.S. Anderson, E.L. Carls, P.J. Mainhardt, W.M. Swift, J.M. Wheeldon, S. Brooks, A.J. Minchener, and J. Stringer: *J. Eng. Gas Turbines Power*, 1988, vol. 109, p. 298.

2. S. Hogmark, A. Hamersten, and S. Soldberg: *Proc. 6th Int. Conf. on Erosion by Liquid and Solid Impact*, Cambridge, United Kingdom, 1983, paper no. 37.
3. C.T. Kang, F.S. Pettit, and N. Birks: *Metall. Trans. A*, 1987, vol. 18, p. 1785.
4. G. Sundararajan: *Wear*, 1991, vol. 145, p. 283.
5. D.J. Stephenson and J.R. Nicholls: *Plant Corrosion: Prediction of Materials Performance*, Ellis Horwood, London, 1987, pp. 313-24.
6. V.K. Sethi and I.G. Wright: *Proc. Conf. on Erosion-Corrosion-Wear of Materials at Elevated Temperatures*, Berkeley, CA, 1990, National Association of Corrosion Engineers, Houston, TX, 1991, p. 18-1.
7. M.M. Stack, J.G. Chacón-Nava, and F.H. Stott: *Wear*, 1995, vol. 180, p. 91.
8. C.E. Witherell: *Proc. 10th Int. Conf. on Fluidized Bed Combustion*, San Francisco, CA, 1989.
9. A.J. Ninham, I.M. Hutchings, and J.A. Little: *Corrosion/89*, NACE, Houston, TX, 1989, paper no. 554.
10. F.H. Stott, S.W. Green, and G.C. Wood: *Mater. Sci. Eng. A*, 1989, vol. 121, p. 611.
11. S.S. MacAdam and J. Stringer: *Corrosion*, 1993, vol. 49, p. 156.
12. M.M. Stack, F.H. Stott, and G.C. Wood: *Mater. Sci. Technol.*, 1991, vol. 7, p. 1128.
13. R.L. Klueth and R.E. Oakes Jr.: *Trans ASME J. Eng. Mater. Technol.*, 1977, vol. 12, p. 350.
14. V.K. Sethi and R. Corey: *Proc. 7th Int. Conf. on Erosion by Liquid and Solid Impact*, Cambridge, United Kingdom, 1987, paper no. 73.
15. A.J. Ninham, J.A. Little, and I.M. Hutchings: *Mater. Sci. Technol.*, 1990, vol. 6, p. 69.
16. J. Paidassi: *L'Oxidation des Metaux V-II*, Gauthier-Villars, Paris, 1964.
17. I.G. Wright, M.A. Rocazella, and V. Nagarajan: *EPRI Workshop on Wastage on In-Bed Surfaces of FBC's*, VIII, Argonne, Ill, 1987, paper no. 5.5.
18. B.Q. Wang, G.Q. Geng, and A.V. Levy: *Corrosion/92*, NACE, Houston, TX, 1992, paper no. 129.
19. M. Olsson, P. Tarkpea, and V. Engman: *Tribology Int.*, 1995, vol. 28, p. 107.