

# HIGH TEMPERATURE EROSION-OXIDATION BEHAVIOR OF STEELS<sup>1</sup>

Stela M.C.Fernandes<sup>2</sup>  
Olandir V. Correa<sup>3</sup>  
Lalgudi Ramanathan<sup>4</sup>

## Abstracts

The high temperature erosion-oxidation (E-O) behavior of steels AISI 1020, 304, 310, and 410 were determined. These steels were selected to also evaluate the effect of chromium content on their E-O resistance. A test rig in which a specimen assembly was rotated through a fluidized bed of erodent particles was used to determine the E-O behavior. Alumina powder (200 $\mu$ m) was used as the erodent. The E-O tests were carried out in the temperature range 25 - 600°C, with average particle impact velocities of 3.5 and 15 ms<sup>-1</sup> and impact angle of 90°. The E-O wastage of the steels exposed to low velocity particle impact was low but increased with temperature above 300° C. The E-O wastage of the different steels exposed to high velocity particle impact velocity was quite similar. The wastage increased with increase in temperature above 500° C. The increases in E-O wastage of the steels observed at temperatures above 300° C, 400° C or 500° C, depending on the steel, are due mainly to a transition in the dominant wastage process, from 'erosion' to 'erosion-oxidation'.

**Key words:** Oxidation; Erosion; Erosion-oxidation; Wastage; Steels.

## COMPORTAMENTO DA EROSÃO - OXIDAÇÃO DE AÇOS EM TEMPERATURAS ELEVADAS

### Resumo

Foram determinados os comportamentos da erosão – oxidação (E-O) dos aços AISI 1020, 304, 310, e 410. Estes aços foram selecionados para avaliar também o efeito do teor do cromo sobre a resistência E-O. Foi utilizado um aparato no qual um conjunto de corpos de prova foram sujeitos a rotação num leito de partículas erosivas fluidizadas. Foram utilizados pós de alumina (200 $\mu$ m) como partículas erosivas. Os ensaios de E-O foram realizados na faixa de temperatura de 25 - 600°C, com velocidade media de impacto das partículas de 3.5 a 15 ms<sup>-1</sup> e com angulo de impacto de 90°. Desgaste E-O dos aços expostas a partículas com baixa velocidade de impacto estava baixo, mas aumentou com aumento em temperatura ate 300° C. O desgaste E-O dos diversos aços foi similar quando exposta a partículas erosivas a velocidade alta. O desgaste aumentou com aumento em temperatura acima de 500° C. O aumento em desgaste E-O, dependendo do aço, observados a temperaturas acima de 300° C, 400° C ou 500° C, foi devido a uma transição, de erosão para erosão – oxidação, no processo dominante de desgaste.

**Palavras chave:** Oxidação; Erosão; Erosão-oxidação; Desgaste; Aços.

<sup>1</sup> Technical contribution to 62nd ABM - International Annual Congress, July 23<sup>rd</sup> to 27<sup>th</sup>, 2007, Vitória - ES - Brazil

<sup>2</sup> Dra. IPEN, Av. Prof. Lineu Prestes 2242, São Paulo, Brasil.

<sup>3</sup> Técnico, IPEN, Av. Prof. Lineu Prestes 2242, São Paulo, Brasil.

<sup>4</sup> Ph.D, Gerente do CCTM, IPEN, Av. Prof. Lineu Prestes 2242, São Paulo, Brasil.

## 1 INTRODUCTION

The erosion behavior of metallic materials and ceramics at room temperature has been extensively studied.<sup>(1-3)</sup> Nevertheless, a number of questions regarding correlations between erosion properties and physical parameters of the materials remain unanswered. A vast amount of information is available about the oxidation behavior of various metals and alloys at high temperatures. However, only limited information is available about the conjoint effect of erosion and oxidation at high temperatures. The results of some of the erosion-oxidation (E-O) studies demonstrate that there is synergy between erosion and oxidation. This indicates that the degradation caused by E-O can be greater than the sum of degradation caused by erosion and oxidation processes operating separately.<sup>(4-6)</sup> There are also references to surface oxide scales inhibiting erosion.<sup>(7)</sup> That is, the wastage rate under E-O conditions can be lower than that in the absence of oxidation. These contrary observations have generated, in recent years, much attention about E-O processes.

E-O interactions have been described in terms of regimes. Kang et al. proposed the existence of four regimes as a function of increasing temperature, based on E-O studies of pure metals.<sup>(8)</sup> These regimes were termed: (a) erosion of metal, which predominated at low temperatures; (b) oxidation affected erosion, where the oxide and the metal eroded; (c) erosion-enhanced oxidation, during which more oxide formed as it was eroded and (d) oxide erosion, where only the oxide eroded. Modifications to these regimes and other interpretations about the existence of a variety of other sub E-O regimes have been proposed.<sup>(9,10)</sup> Definition of E-O regimes has varied significantly, both in the number of regimes that have been proposed as well as in the criteria for defining transitions.<sup>(11)</sup> Justifications for the various regimes depended on the E-O conditions and experimental evidence put forth to support the transitions. This signifies that there is potentially a number of interaction regimes depending on the criteria used to define the transitions.

Adequate procedures to select materials to resist E-O degradation at high temperatures are presently not available. Presently, a variety of metallic materials, composites, cermets and ceramic materials are used in industrial applications where E-O conditions prevail. The metallic materials include readily available alloys such as carbon steels, stainless steels, rare earth containing chromium dioxide or alumina forming alloys and hard material coated alloys. The criteria often used in many industries to select alloys for components subject to E-O conditions are hardness, cost and availability.

This paper presents the high temperature erosion-oxidation behavior of a variety of readily available steels such as AISI 1020, 304, 310 and 410. The E-O measurements were made in a test rig in the temperature range 25°C - 600°C, using alumina particles as the erodent at impact velocities of 3.5 and 15 ms<sup>-1</sup>.

## 2 METHODS AND MATERIALS

The chemical composition of the steels AISI 1020, 304, 310 and 410, used in this investigation is shown in Table 1. Specimens for the E-O tests were cut to size from steel sheets, cleaned and degreased ultrasonically in acetone.

**Table 1.** Steel composition determined by x-ray fluorescence spectroscopy.

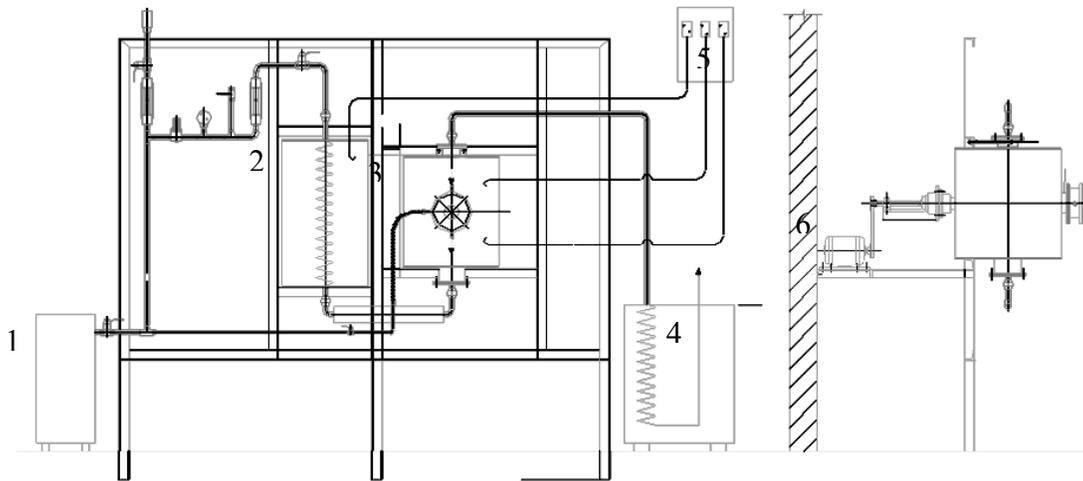
Steel AISI	Elements (wt%)							
	Cr	Ni	Mo	Mn	Si	P	Cu	Fe
1020	-	-	-	0.33	-	-	-	Balance
410	11.5	0.18	-	0.14	0.5	0.4	-	Balance
304	18.7	8.0	0.03	1.4	0.6	0.04	0.09	Balance
310	24.1	19.1	0.07	1.7	0.5	-	0.01	Balance

A schematic diagram of the E-O test rig is shown in Figure. 1. In this rig a specimen assembly was rotated through a fluidized bed of erodent particles. Alumina powder with particles in the size range 212-150  $\mu\text{m}$  was used as the erodent. The fluidized bed of particles was obtained by pumping pre-heated air through a porous plate supporting a bed of erodent particles. Fluidization of the erodent particles was done within a furnace and the erodent impact velocity on the test specimens was controlled by a motor that rotated the specimen assembly.

The E-O test specimens were weighed and fixed with AISI 310 screws to the specimen holder in the E-O test rig. The specimens were positioned at the end of a crossed specimen holder. The E-O test conditions were: 25°C - 600°C, average erodent impact velocities of 3.5 and 15  $\text{ms}^{-1}$  and impact angle of 90°. After the tests, the specimens were weighed, examined in a scanning electron microscope, the surface reaction products analyzed by EDS and the surface roughness as well as hardness measured.

### 3 RESULTS AND DISCUSSION

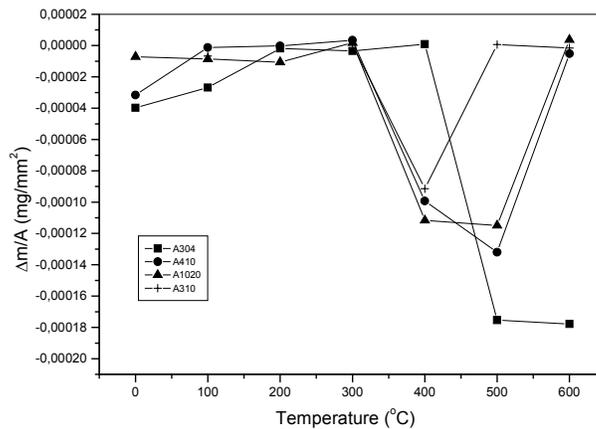
The results of preliminary isothermal oxidation studies of these steels revealed a significantly higher oxidation rate for AISI 1020 compared to the other steels and was due primarily to the formation of  $\text{Fe}_3\text{O}_4$ . The other steels exhibited parabolic oxidation behavior and the weight gain was due mainly to formation of  $\text{Fe}_3\text{O}_4$  and  $\text{Cr}_2\text{O}_3$  on AISI 410 and mainly  $\text{Cr}_2\text{O}_3$  on AISI 304 and 310. Comparison of the oxidation behavior of the steels also revealed that oxidation rates decreased with increase in chromium content of the steel.



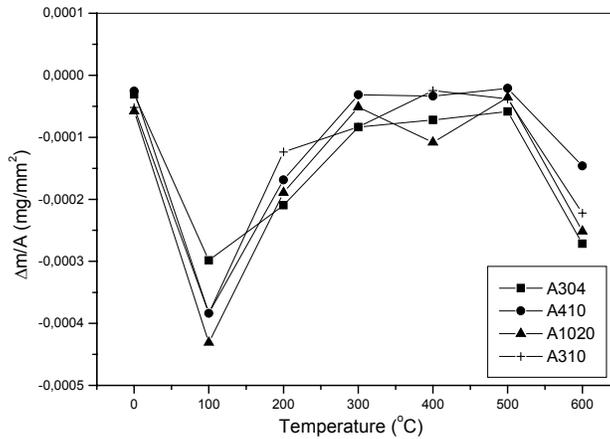
**Figure 1.** Schematic diagram of the erosion-oxidation test rig: 1- compressor; 2- pre-heating furnace; 3- E-O furnace; 4- system for retaining particles and for cooling; 5- control panel for controlling the motor and the furnaces; 6- motor to rotate the specimens through the bed of erodent particles in the furnace.

### 3.1 Erosion-oxidation Behavior

The E-O behavior, expressed as wastage, or mass loss, of the four steels as a function of temperature is shown in Figures 2 and 3. The steels were exposed to the E-O environment for 5 hours at 25°, 100°, 200°, 300°, 400°, 500° and 600° C.

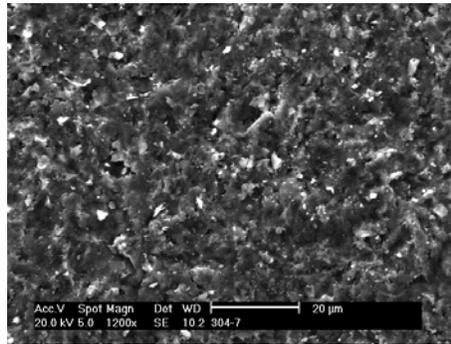


**Figure 2.** Wastage of the steels exposed for 5 h to low particle impact velocity as a function of temperature.



**Figure 3.** Wastage of the steels exposed for 5 h to high particle impact velocity as a function of temperature.

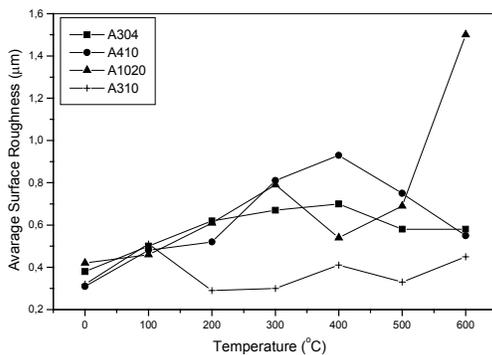
In Figure 2, it can be seen that wastage of the different steels was low up to 300° C. The wastage of AISI 1020 and AISI 410 increased above 300° C and then decreased above 500° C. The wastage of AISI 304 was very low up to 400° C, and it then increased. The wastage of AISI 310 remained quite low till 300° C and then increased before decreasing again above 400° C. Overall variations in wastage observed at low particle impact velocity is very low and is evident from the weight loss values on the y-axis of the graph. At high particle impact velocity shown in Figure 3, all steels revealed marked wastage at 100° C and this decreased with increase in temperature up to 500° C. The wastage of all the steels again increased with increase in temperature to 600° C. The wastage at 100° C in this figure can be attributed to loss of air-formed surface oxide and base metal. With increase in temperature, the wastage decrease is due to formation of surface oxide. That is, the weight gain due to oxide formation is more than weight loss caused by oxide removal by particle impact. At temperatures beyond 500° C the net weight loss increases and is due to loss of the oxide as it is formed and loss of base metal. The oxide formed on AISI 1020 is mainly  $\text{Fe}_2\text{O}_3$  at low temperatures and  $\text{FeO}$  at higher temperatures. The former is more ductile and therefore more resilient towards particle impact. On the other hand the latter oxide,  $\text{FeO}$  is brittle and is easily removed. On the other Cr containing alloys, depending on the Cr content the surface oxide is a mix of iron and chromium oxides. In the initial stages the oxide formed is mainly iron oxide and subsequently the outer layers consist of Cr oxide. The outer Fe oxide is quickly removed by particle impact leaving behind the more resistant but thin layer of chromium dioxide close to the alloy interface. This accounts for the decreased wastage with increase in temperature up to 500° C. At temperatures above 600° C the wastage increase could be attributed to removal of Cr oxide and the base metal.



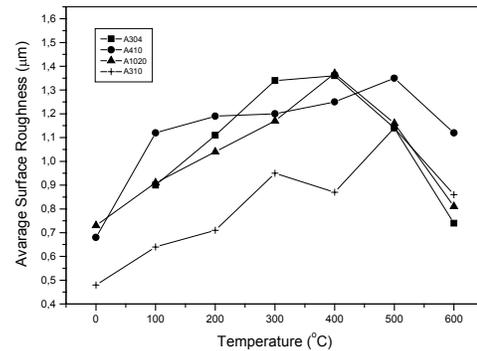
**Figure 4.** Surface of AISI 304 exposed for 5 hours to E-O environment at 300° C.

Alumina inclusions were observed on the surface of many specimens following E-O exposure as shown in Figure.4. EDS spectra of these surfaces confirmed the presence of alumina particles. Some of the scatter in the data at low impact velocity in Figure 2 could be related to weight increase due to particle incorporation. Embedded particles were observed on the surfaces of some steels, especially the austenitic steels.

Figure. 5 shows the average surface roughness, 'Ra', of the steel specimens as a function of E-O temperature. The average surface roughness increased with temperature. The Ra of steels with low chromium content, such as AISI 1020 and 410 after 5 h of exposure to the E-O environment at 300° C was higher than Ra of the AISI 304 and 310 exposed for the same duration to the E-O environment at 400° C. In fact the Ra of AISI 310, which forms only chromium dioxide was much lower than the Ra of the other steels exposed to the different E-O conditions of temperature and particle impact velocity. This indicated the marked reduction in Ra with formation of  $Cr_2O_3$  on the surface of steels with higher Cr content.



(a)



(b)

**Figure 5.** Average surface roughness 'Ra' of the steel specimens exposed for 5 h to the E-O environment at (a) low and (b) high particle impact velocity.

To throw more light on the erosion-oxidation data obtained at the two particle impact velocities the hardness of the Cr containing steel specimens exposed for 5h at 500° C to (a) no particles; (b) low velocity particle impact and (c) high velocity particle impact were determined. The results are shown in Table 2. This table reveals that with particle impact the surface hardness of AISI 410 increases from 71 to 102. Increase in particle

impact velocity did not affect the surface hardness of this steel. This is due probably to ductile to brittle transition of this steel, that normally takes place around 500° C depending on its Cr and C contents. The 18% Cr containing AISI 304 and the 25%Cr containing AISI 310 did not show any significant change in hardness caused by particle impact.

**Table 2.** Vickers microhardness of steel specimens exposed for 5h at 500° C in the E-C rig to: (a) no particles; (b) low velocity particle impact and (c) high velocity particle impact.

Steels (AISI)	Vickers microhardness (g/mm <sup>2</sup> )		
	No particle impact	Low velocity particle impact (ms <sup>-1</sup> )	High velocity particle impact (ms <sup>-1</sup> )
410 (12%Cr)	71	102	103
304 (18%Cr)	72	72	72
310 (25%Cr)	92	82.5	95

### 3.2 Wastage Behavior of the Steels

At low temperatures, erosion of metal is the dominant process and wastage is said to be “erosion-dominated”.<sup>(11-13)</sup> As the temperature increases, oxide formation increases. If the oxide is less erosion resistant than the underlying metal substrate, it is easily removed, together with the underlying metal, between successive erosive events, as the temperature is increased. Since the rate of oxidation increases rapidly with increase in temperature, this means that at a specific temperature, the wastage due to loss of oxide scale is greater than that due to loss of metal. This marks the transition to “erosion-corrosion dominated” behavior as observed in Figure 2 at temperatures above 300° C for AISI 1020 and 410 and above 400° C for AISI 304. If most or all the scale continues to be removed on particle impaction, the wastage rate increases, as the oxidation rate increases with temperature. This is more evident from the wastage curves of the steels at the higher particle impact velocity in Figure 3. A steady decrease in wastage of the different steels is followed by increase in wastage at temperatures beyond 500° C.

The composition of the steel influences the composition of the scale and thus the erosion resistance. The ability to accommodate deformation and absorb impact energy at high temperature is a function of scale composition, with iron oxides more ductile than chromium oxides. The kinetics of scale growth is also dictated by alloy composition. Chromium dioxide forms on the high chromium containing alloys, and a transition to parabolic behavior occurs at high temperatures. On AISI 1020, at low temperatures, Fe<sub>3</sub>O<sub>4</sub> scale forms and this protects to some extent. At higher temperatures, the scale formed is mainly FeO and this is not protective. The oxidation rate is very high and metal loss also high, compared with that at lower temperatures, where FeO scale do not form.

## 4 CONCLUSIONS

1. The E-O wastage of AISI 1020 and 410 exposed to particles with low impact velocity was low up to 300° C and thereafter increased with increase in temperature. The E-O wastage of AISI 304 under similar conditions also increased at temperatures beyond 400° C. However, the E-O wastage of the high Cr containing AISI 310 decreased to very low values.

2. The E-O wastage behavior of the different steels exposed to high particle impact velocity was quite similar. The wastage increased with increase in temperature to 100° C and thereafter decreased with increase in temperature to 500° C. At temperatures above 500° C the wastage increased again.
3. The increases in E-O wastage of the steels observed at temperatures around 300° C and 400° C upon exposure to low velocity particle impact and above 500° C upon exposure to high velocity particle impact are due mainly to a transition in the dominant wastage process, from 'erosion' to 'erosion-oxidation'.

## REFERENCES

- 1 SHEWMON, P.; SUNDERARAJAN, G. The erosion of metals, **Annual Review of Materials Science**, v. 13, p. 301, 1983.
- 2 BITTAR, J.G.A. A study of erosion phenomena, Part I. **Wear**, v. 6, p.5.1963.
- 3 HUTCHINGS, I.M.; WINTER, R.E. Particle erosion of ductile metals – mechanism of material removal, **Wear**, v. 27, p.121, 1974.
- 4 WRIGHT, I.G.; NAGARAJAN, V.; HERCHENROEDER, R.B. Some factors affecting solid particle erosion/corrosion of metals and alloys, in Fall Meeting, Corrosion-Erosion Behavior of Materials', K. Natesan, ed., St. Louis, MO1978.**Proceedings...**
- 5 LEVY, A.V.; ZAMBELLI, G. Particulate erosion of NiO scales, **Wear**, v. 68, p.305, 1981.
- 6 TABAKOFF, W. Experimental study on the effects of specimen sizes on erosion, **Wear**, v. 86, p.65, 1983.
- 7 STACK, M.M.; LEKATOS, S.; STOTT, F.H. Erosion-corrosion regimes: number, nomenclature and justification, **Tribology International**, v. 28, p.445,1995.
- 8 KANG, C.T.; PETTIT, F.S.; BIRKS, N. Mechanisms in the simultaneous erosion-oxidation attack of nickel and cobalt at high temperatures, **Metallurgical Transactions**, v. 18A, p.1785, 1987.
- 9 RISHEL, D.M.; PETTIT, F.S.; BIRKS, N. Some principle mechanisms in the simultaneous erosion and corrosion attack of metals at high temperatures, **Materials Science and Engineering A**, v. 143, p.197, 1991.
- 10 STEPHENSON, D.J.; NICHOLLS, J.R. Modeling erosive wear, **Corrosion Science**, v. 35, p.1015, 1993.
- 11 STACK, M.M.; STOTT, F.H.; WOOD, G.C. Review of mechanisms of erosion-corrosion of alloys at elevated temperatures, **Wear**, v. 162-164(B), p.706, 1993.
- 12 KUNIOSHI, C.T.; CORREA, O.V.; RAMANATHAN L.V. Erosion-oxidation behavior of thermal sprayed Ni20Cr alloy and WC and Cr<sub>3</sub>C<sub>2</sub> cermet coatings, **Materials Research**, v. 8, 2, p.125, 2005.
- 13 KUNIOSHI, C.T.; CORREA, O.V.; RAMANATHAN L.V. High temperature oxidation and erosion-oxidation behaviour of HVOF sprayed Ni-20Cr, WC-20Cr-7Ni and Cr<sub>3</sub>C<sub>2</sub>-Ni-20Cr coatings, **Surface Engineering**, v. 22, 2, p. 121, 2006.