Study of Solid Particle Erosion Behaviour of SS 304 at Room Temperature

Mayank Patel¹, Darshan Patel¹, S. Sekar *, P. B. Tailor¹, P. V. Ramana¹

Department of Mechanical Engineering, Sardar Vallabhbhai Institute of Technology, Vasad, 388306, India

Abstract

Erosion is one of the major problems in many engineering systems including power generation units, steam/jet turbines, chemical processing equipments, and aircraft engines. In the present study erosion test were conducted using air-jet erosion test rig on boiler tube steel SS 304. The impact velocity was 40m/s, the impingement angle was 30° and 90° on SS 304 at room temperature. Alumina particles of size 50 microns were used as the erodent. The initial and final weight of the specimens were taken using electronic weighing machine having a resolution of 0.01mg. Erosion rate was determined as the ratio of weight loss of the material to the weight of eroding particles. Scanning electron microscope (SEM), equipped with an energy dispersive X-ray analyser (EDAX) was used to analyse the eroded surfaces. Results indicated that SS 304 showed higher erosion rate at 30° as compared to 90° impact angle, indicating ductile mode of erosion.

Keywords: Erosion; Erosion rate; SS 304; Solid particle erosion

1. Introduction

Boiler tube erosion is one of the significant problem that is faced by all power generations units that operates on combustion of fossils fuels. Erosion, high temperature wear of heat transfer pipes and other structural materials in coal boilers are recognized as being the main cause of downtime at power generating plants, accounting for 50% to 75% of the total arrest time [1, 2]. Maintenance costs for replacing broken pipes in the same installations are also
very high, and can be estimated at up to 54% of the total production costs [3]. Coal is a complex fuel that contains varying amount of sulphur and a substantial fraction of non-combustible mineral constituents, commonly called ash. The coal used in Indian power stations contains ash (about 50%), consisting of abrasive mineral species (hard quartz up to 15%) which cause erosion of tubes. During the combustion of coal, the mineral matter is transformed into fly ash, which is deposited on heat transfer surfaces of boilers. The heat transfer tubes of the boilers used in thermal power plants are subjected to intolerable levels of surface degradation by means of the combined cause of erosion–corrosion mechanism, ensuing in the tube wall thinning and untimely failure. High temperature surface oxidation and erosion by the impact of fly ash and unburnt carbon particles are the main problems in coal fired boilers [4]. More than one quarter of all the boiler tube failures worldwide are caused by fly ash erosion. In a case study done by Dr. Satya Prakash, IIT Roorkee of a coal fired boiler of a power plant in north western region of India, it is reported that out of 89 failures occurring in one year, 50 failures were found to be due to erosion and hot corrosion [5].

Erosion is defined as progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multi-component fluid, or impinging liquid or solid particles [6]. Solid particle erosion implies the removal of material from component surfaces due to successive impact of hard particles travelling at substantial velocities. Solid particle erosion is an important material degradation mechanism encountered in a number of engineering systems such as thermal power plants, aircraft gas turbine engines, pneumatic bulk transport systems, coal liquefaction/gasification plants and ore or coal slurry pipe lines.[7]

Stainless steels (SS) are widely used in different components working under combined corrosive and erosive effects. Amongst SS, austenitic SS are preferred to martensitic SS, due to their higher corrosion resistance, even though their mechanical strength is less [8]. SS-304 is extensively used for boiler tube applications as it has very good oxidation and corrosion resistance. Although erosion behaviour of SS-304 has been studied by many researchers, there is still lack understanding on how it behaves under different erosive conditions.

In the present investigation, erosion studies were conducted on uncoated AISI SS 304 specimens at room temperature. The erosion experiments were carried out using an air-jet erosion test rig at 40m/s velocity and two different impingement angles. Scanning electron microscope (SEM), equipped with an energy dispersive X-ray analyzer (EDAX) was used to analyse the eroded surfaces.

2. Experimental procedure

2.1 Substrate material

AISI-304 grade boiler steel has been selected as substrate. Specimens of approximate dimensions of 25 mm x 20 mm x 5 mm were cut and then polished with emery papers of 220, 400, 600 grit sizes, subsequently on 1/0, 2/0, 3/0,4/0,5/0 and 6/0 grades to obtain mirror polished surface of the substrate. The chemical composition of SS 304 is shown in Table 1

<table>
<thead>
<tr>
<th>Steel</th>
<th>Fe</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Ni</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 304</td>
<td>Bal.</td>
<td>0.08</td>
<td>2.00</td>
<td>0.045</td>
<td>0.03</td>
<td>1.00</td>
<td>18-20</td>
<td>-</td>
<td>-</td>
<td>8-12</td>
<td>-</td>
</tr>
</tbody>
</table>

2.2 Room temperature erosion tests

Erosion testing as carried out using Air Jet Erosion Test Rig, Model No TR-470 (Fig. 1) at the Sardar Vallabhbhai Institute of Technology (SVIT), Vasad, Gujarat, India. The erosion tests were performed at room temperature. The rig consisted of an air compressor, a particle feeder hopper, a mixing chamber. Dry compressed air was mixed with
the particles, which were fed at a constant rate from hopper in the mixing chamber and then accelerated by passing the mixture through a tungsten carbide converging nozzle of 1.5 mm diameter. These accelerated particles impacted the specimen, which could be held at various angles with respect to the impacting particles using an adjustable sample holder. The feed rate of the particles and the pressure could be controlled by rotation of the two knobs, Set Discharge and Air Regulator on the controller unit respectively. The impact velocities of the particles could be varied by varying the pressure of the compressed air.

The erosion test conditions utilized in the present study are listed in Table 2. A standard test procedure was employed for each erosion test. The samples were cleaned in acetone, dried, weighed to an accuracy of 0.01 mg using an electronic balance, eroded in the test rig for 5 min and then weighed again to determine weight loss. The ratio of this weight loss to the weight of the eroding particles causing the loss (i.e., testing time × particle feed rate) was then computed as the dimensionless incremental erosion rate. This procedure was repeated until the erosion rate attained a constant steady-state value as per ASTM standard G76-95 (2000) [9].

![Fig. 1. Air Jet Erosion Test Rig, Model No TR-470](image)
Table 2 Erosion conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Particulars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erodent material</td>
<td>Alumina particles (irregular shape)</td>
</tr>
<tr>
<td>Particle size (µm)</td>
<td>50±2</td>
</tr>
<tr>
<td>Particle velocity (m/s)</td>
<td>40±2</td>
</tr>
<tr>
<td>Air pressure (kg/cm²)</td>
<td>3.0</td>
</tr>
<tr>
<td>Erodent feed rate (g/min)</td>
<td>5±0.4</td>
</tr>
<tr>
<td>Impact angle (°)</td>
<td>30 and 90</td>
</tr>
<tr>
<td>Test temperature</td>
<td>Room temperature</td>
</tr>
<tr>
<td>Nozzle diameter (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Test time (min)</td>
<td>Cycles of 5 min</td>
</tr>
</tbody>
</table>

3. Results & Discussions

3.1. Macrograph of eroded samples

The surface macrographs of the eroded SS 304 samples at 30° and 90° impact angles are shown in Fig. 3. In both the samples, the erosion starts at the centre first, and then proceeds towards the edges of the samples. The eroded region formed by the 90° impact angle is of circular shape whereas at a 30° impact angle the eroded region has an elliptical shape. The macrographs of eroded samples clearly shows that three zones were created; the first zone is the central area where most of the material was eroded, the second zone is the area where somewhat less material was eroded and the third zone where least amount of material was eroded.

Fig. 2. SEM micrograph of alumina particles

Fig. 3. Macrographs of uncoated samples D=5 g/min V=40 m/s a) 30° b) 90°
3.2 Erosion rate

Fig. 4 shows the effect of impingement angle (30° and 90°) on erosion rate at an impact velocity of 40 m/s for specimen of SS 304. The erosion rates at 30° impact angle were somewhat higher than at 90° impact angle. From the macrographs it can be seen that erosion is higher during the initial cycles of study, thereafter a steady state erosion rate is achieved at 30° impact angle. The erosion in ductile material is higher at lower impact angles because, the impacting particles produces a ploughing effect and the material is removed in the form of scoops. On the other hand, at higher impact angles most of the kinetic energy of the impacting particles is dissipated in plastically deforming the material, without actually removing it [10, 11].

3.3 SEM analysis of eroded samples

A scanning electron microscope (SEM) [JEOL (JSM-5610 LV)] with EDAX attachment was used for surface SEM/EDAX analysis of the eroded coatings. Fig. 5 and 6 clearly shows the craters formed by the impacts of erodent particles on the surface of SS 304. It has been observed that plastic deformation occurs with formation of craters and lips. The eroded samples at impact of 30° shown that the material removal occurs by the ploughing mechanism (Fig 5d). Formation of craters is more in case of 90° impact angle as seen in Fig. 6a. The erosion occurred by the platelet mechanism in the case of substrate material similar to that described by Hutchings and Levy [12]. They reported that in the steady state condition, the three phases occur simultaneously at different locations over the surface. In the initial phase the impacting particle forms a crater, and material is extruded or displaced from the crater to form a raised lip or mound. In the second phase the displaced metal is deformed by subsequent impacts; this may lead to lateral displacement of the material, and can be accompanied by some ductile fracture in heavily strained regions. Finally, after a relatively few impacts, the displaced material becomes so severely strained that it is detached from the surface by ductile fracture [12].
Fig. 5. Scanning electron micrographs of eroded SS 304 at a 30° impact angle

Fig. 6. Scanning electron micrographs of eroded SS 304 at a 90° impact angle
3.4 SEM/EDAX analysis

The surface EDAX analysis of eroded SS-304 surface at 30° and 90° impact angles is shown in Fig 7. The eroded surface shows mainly the presence of Fe, Cr, Ni, O and Al. The percentage of Fe, Cr and Ni shown by the EDAX analysis is in conformance with the chemical composition of SS-304 shown in Table 1. The presence of Al along with O clearly indicates that the erodent (alumina) has incrusted the substrate material. The amount of Al present on the eroded surface of SS 304 is almost twice at 30° as compared to 90° impact angle (Fig. 7a and b). The lower amount of Al at 90° impact angle may be due to strain hardening of SS-304 by impacting erodent particles, which may have reduced the plasticity of SS-304 as compared to same material at 30° impact angle. At lower impact angles (30°) the material removal is more like cutting tool action, wherein the erodent particle plastically deform the material by ploughing effect and shear deformation.

4. Conclusions

Based on the conducted experiments the following specific conclusions can be drawn:

- Study of erosion rates of SS 304 at velocity of 40m/s have been determined as a function of two impact angles, 30° and 90° at the room temperature.
- Erosion takes place through plastic deformation of material along with the formation of craters and lips.
- The eroded samples at impact of 30° shows that the material removal occurs by the ploughing effect and shear mechanism.
- The erosion rate of the SS 304 at impingement angle 30° is little higher than the 90° angle and hence SS-304 exhibits ductile erosion mode.
Acknowledgements

The authors would like to acknowledged GUJCOST, Gandhinagar, Gujarat, India for providing the financial support under the Minor Research Project (MRP). Also they would like to thank the Metallurgical and Materials Engineering Department, M. S. University of Baroda, for allowing utilizing the SEM/EDAX facility.

References