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Erosion behaviour of boiler component materials at room temperature and 400 °C temperature

Prashant Kumar Singh and S B Mishra
Department of Mechanical Engineering, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, UP—211004, India
E-mail: prashantobra2k6@gmail.com

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Abstract
Degradation of boiler tube components in Indian thermal power plants is mainly done through solid particle erosion due to exposure in erosive ash environment. Some important parameter such as hardness, erodent velocity, temperature, impact angle, shape and size are majorly affected the erosion wear. In this study, the erosion wear behaviour of SAE 208 grade steel, SAE213-T12 boiler steel, SAE213-T91 boiler steel and IS 2062 structural steel were investigated using an air jet erosion test rig. The erosion tests were carried out at the impact angles of 30° and 90°, impact velocity of 42.3 m/s at room temperature and 400 °C. The position of sample holder was adjusted in such a way that erosion wear scar occur at the central region of the samples. For each experiment, the erosion test was continued until the steady state erosion rate was achieved as per ASTM standard. The variation in erosion rate data has been plotted against cumulative mass of erodent for boiler and structural steel samples. The steady state erosion rates for different steel samples are calculated and compared. The surfaces of tested samples are analyzed using scanning electron microscopy to understand the erosion mechanism. The results showed that the ductile behaviour of erosion mechanism is dominated at both room temperature and 400 °C temperature. Mechanism involved at 90° impact angle is plastic deformation with formation of craters and at 30° impact angle is cutting and ploughing.

1. Introduction

Coal-fired power plants are the traditional and major source of electric power generation in India. There are four major divisions in coal-fired thermal power plant, which include turbine, boiler, coal handling system and electrical energy handling system. Amongst these divisions, boiler is a crucial and critical part of coal-fired power plant. The major components of the boiler are boiler walls, economisers, air-heaters and super-heater tubes [1]. The fly ash particles entrained in the fluidized bed impact to the surface of boiler tubes and are deposited on the boiler tube components causing erosion wear, oxidation and hot corrosion [2]. In advanced stages of degradation of the components material, the service-life of boilers and its parts get shorten. This requires shut down of the power station unit to replace the damaged parts or components [3]. Erosion wear of the engineering materials is affected by operating conditions including impact angle, particle velocity and temperature; impacting particles properties such as size, shape, density and hardness; and target material properties such as hardness, roughness, strength and toughness, etc [4]. Among these parameters, impact angle and temperature play a vital role in erosion process. There is no universal model to predict the effectiveness of these parameters. Experimental study of these parameters on erosion process is one of the effective ways to analyse the erosion mechanism. Okonkwo et al [5] studied the erosion behaviour of pipeline steel at particle speed ranging 20–80 m/s and impact angle at 30° and 90°. The authors have found that ploughing mechanism is dominated at 90° impact angle while cutting at 30° impact angle. Antonov et al [6] investigated the behaviour of seven graded steels under solid particle impacts at room temperature and elevated temperature and found that oxidation is more influence the erosion condition at elevated temperature under the oblique angle of impact. Patel et al [7] studied
of the boiler and structural steels.

| Elements | Name of steel | C  | Si  | Mn  | P   | Co  | Cr  | Mo  | Ni  | V  | Fe  |
|----------|---------------|----|-----|-----|-----|-----|-----|-----|-----|----|-----|
|          | SAE213-T91    | 0.098 | 0.256 | 0.434 | 0.018 | 0.019 | 8.523 | 0.995 | 0.072 | 0.22 | Bal. |
|          | SAE213-T12    | 0.08 | 0.286 | 0.443 | 0.025 | 0.011 | 8.87 | 0.99 | 0.058 | 0.225 | Bal. |
|          | SAE208 steel  | 0.161 | 0.241 | 1.003 | 0.005 | 0.003 | 0.031 | 0.007 | 0.006 | 0.002 | Bal. |
|          | IS 2062 Structural steel | 0.23 | 0.4 | 1.5 | | | | | | | Bal. |

The solid particle erosion behaviour of SS304 at room temperature and found that the higher erosion occur at 30° as compared to 90° impact angle which indicated ductile mode of erosion mechanism. Islam et al [8] evaluated the erosion rate of AISI1018 and AISI 1080 steel with varying particle velocity and impact angles and analysed that the erosion rate is increases with increasing particle velocity and decreases with increasing impact angle. Nagraj et al [9] studied the erosion behaviour of CY5SnBiM cast alloy at room temperature. The author found that impact angle is more dominant parameter in comparison to impingement velocity while the erosion test is occurred. Wear scars are found to be elliptical mostly at 30°, 60°, 90° and circular at 90°. Shimizu et al [10] evaluated the erosion characteristic of high Cr cast iron at 1173 K and found that at high temperature, more Cr content having better erosion resistance. Zaragoza-Granadou et al [11] studied the microstructural characteristic of eroded surface of AISI 310 steel and found that mostly the sections are affected by plastic deformation, ploughing, cracking and flaking.

Most of the engineering components such as fluid bed combustors, boiler tubes, turbines, heat exchangers, coal gasifier, burners and combustion chambers are exposed to solid particle erosion at room temperature as well as elevated temperature. Already efforts have been made for solid particle erosion study with the different parameters such as impact velocity, impact angle, erodent size and shape and temperature [12–16]. Yet, further study is required to understand the depth knowledge of erosion mechanism in terms of impact angle and temperature which are mostly affect the material surface. In the present work, the aim of the author is to contribute to knowledge of solid particle erosion resistance of boiler steels at room temperature and 400 °C temperature and at 30° and 90° impact angle.

2. Experimentation

Based on the effects of chemical compositions, SAE 213-T12 and SAE 213-T91 grades of chrome steels, SAE 208 low alloy steel and IS2062 structural steel are taken as the substrate/base materials for the present investigation. Structural steels are used in welded, bolted and riveted structures of mineral processing cement industries, power plants, etc where failure due to erosion wear also occurs [17]. The boiler steels and structural steel are procured from All India Metal Corporation, Gulalwadi, Mumbai in tubes form having 10 mm thickness. The elemental compositions (in wt.%) of all the steels have been obtained using an Optical Emission Spectroscopy (LECO-GDS 500A) available at MANIT Bhopal. The actual chemical compositions (wt%) of all the selected boiler steels and structural steel are given in table 1.

Solid particle erosion tests of all the steel samples were conducted by using an air jet erosion tester (TR–471–900 Model, Ducom make) at MNNIT Allahabad, India as shown in figure 1. The standard size of test samples was cut from boiler tubes and structural steel plate by using wire electric discharge machine. An analytical balance (CONTECH CA–228D) having the least count of 0.00001 g was used to measure the weight of the specimens after each test cycle. The erosion test was continued until a constant steady-state erosion rate was achieved [18]. Each specimen was cleaned using an ultrasonic bath before the start of each cycle. The erosion rate was calculated as mass loss per unit weight of impacting erodent particles. The erosion rate (g g⁻¹) is calculated as per ASTM standard [19]. The impact velocity of erodent which is accelerated from the nozzle was measured by using rotating disc method and by controlling the compressed air pressure; the desired impact velocity was obtained. The erosion experiments were carried out considering erosion test parameters as reported in table 2 as per ASTM standard [20]. Alumina is used as erodent material and its morphology and physical properties are given in figure 2 and table 3 respectively.

The surface morphology of the as-sprayed coatings were conducted by using a field emission scanning electron microscope (Carl ZEISS SUPRA 40VP, Germany) under high vacuum for compositional analysis at 20 kV acceleration voltage.
Figure 1. Schematic diagram of the Air Jet Erosion Test Rig.

Table 2. Erosion test parameters.

| Sample size               | 25 × 25 × 5 mm for 90° impingement angle and 25 × 20 × 5 mm for 30° impingement angle |
|----------------------------|---------------------------------------------------------------------------------------|
| Erodent material          | Alumina sand (50 μm)                                                                   |
| Particle velocity         | 40 ± 3 m s⁻¹                                                                          |
| Air pressure              | 0.3 bar                                                                               |
| Erodent discharge rate    | 10 g min⁻¹                                                                             |
| Test duration             | Cycles of 5 min                                                                        |
| Impact angle              | 30° and 90°                                                                           |
| Test temperature          | Room temperature (32 °C–35 °C) and 400 °C                                              |
| Nozzle Diameter           | 1.5 mm                                                                                |

Figure 2 SEM micrograph of Alumina Erodent.
Table 3. Physical properties of aluminum oxide.

| Crystal phase | Alpha |
|---------------|-------|
| Specific gravity | 3.95 g cm$^{-3}$ |
| Melting point | 2000 °C |
| Hardness | 13.39 GPa |
| Particle size | 50 ± 5 μm |
3. Results and discussions

3.1. Erosion wears of SAE213-T12, SAE213-T91, SAE 208 boiler steels and IS 2062 structural steel at room temperature

3.1.1. Visual examination

The macrographs of the SAE 213-T12, SAE 213-T91, SAE 208 boiler steels and IS 2062 structural steel eroded at 30° and 90° impact angles at room temperature are shown in figure 3. The macrographs of the steel samples revealed three zones as can be seen from the surface macrographs; a central zone from where most of the material removal occurred, surrounded by a second zone from where comparatively less amount of material removal occurred and a third outer boundary region where a marginal amount of erosion occurred. The erosion scar produced at 30° impact angle appeared elliptical in shape whereas for 90° impact angle test; it appeared circular in shape.

3.1.2. Room temperature erosion behaviour of different steels eroded at 30° and 90° impact angles

Figure 4 shows the erosion rates of SAE 213-T12 boiler steel, SAE 213-T91 boiler steel, SAE 208 grade steel and IS 2062 structural steel at the impact angle of 30° and at an impact velocity of 42.3 m s⁻¹ under room temperature test condition. During the initial cycles of erosion tests at 30° impact angle, higher variation in erosion rate has
Figure 6. A histogram illustrating the steady-state erosion rates of different boiler steels and structural steel at 30° and 90° impact angles at room temperature.

Figure 7. Surface SEM micrographs of SAE213-T12 boiler steel eroded at room temperature at (a) 30° impact angle and (b) 90° impact angle.
been observed for all the steel samples. IS 2062 structural steel has shown the highest erosion rate whereas SAE 213-T91 boiler steel has shown the lowest erosion rate amongst the tested steels, at 30° impact angle. From the graph, it can be depicted that the erosion rate of IS 2062 structural steel is marginally higher than SAE 208 grade steel. SAE 213-T91 boiler steel has also shown comparative steady behaviour than the other steels eroded at 30° impact angle. Figure 5 depicts the graph of erosion rate against the cumulative mass of the alumina erodent at 90° impact angle and 42.3 m s⁻¹ impact velocity. From the graph, it can be seen that the erosion rate of IS 2062 structural steel and SAE 208 boiler steel are comparatively higher than SAE 213-T91 and SAE 213-T12 boiler steels at 90° impact angle.

From figures 4 and 5, it is apparent that the variation in erosion rate was more upto the sixth cycle and thereafter it became approximately constant at both the angles. The higher variation of erosion rate during the initial cycles might be attributed to non-uniform plastic deformation during those cycles and it continued until the work hardening of material surface occurred due to the subsequent impacts of alumina erodent particles.

Figure 6 shows a histogram illustrating the steady state erosion rate of SAE 213-T12 boiler steel, SAE 213-T91 boiler steel, SAE 208 grade steel and IS 2062 structural steel. The steady-state erosion rates for all the steel samples at 90° impact angle are revealed lower than that at 30° impact angle. This suggests the ductile behaviour of all the tested steels under the tested condition. The steady state erosion rate of SAE 213-T91 boiler steel is found 150% higher at 30° impact angle than that at 90° impact angle. This is followed by SAE 213-T12 boiler steel, where the steady state erosion rate is found 125% higher at 30° impact angle than that at 90° impact angle. The difference in steady state erosion rates of IS 2062 structural steel and SAE 208 boiler steel eroded at 30° and 90° impact angles are comparatively lower, with 22.16% and 18.69% respectively. Hardness value of SAE 213 T12 and SAE T91 boiler steel is much higher than SAE 208 steel and IS 2062 structural steel due to presence of
high Cr content [10]. Figure 6 also represent that high hardend surface has better erosion resistance at both 30° and 90° impact angle.

3.1.3. Morphological examinations of eroded samples
SEM micrograph of SAE213-T12 steel eroded at 30° impact angle shows some ploughing action with lips and craters due to the plastic deformation of the softer steel surface along with cutting marks (figure 7(a)). SEM micrograph of eroded sample at 90° impact angle clearly shows lips and platelets with craters on the severely deformed surface. Some wear debris due to detachment of material by severe action of the abrasive particles is also clearly visible on the eroded surface (figure 7(b)).

Figure 8 depicts the surface SEM micrographs of SAE213-T91 boiler steel after subjecting to erosion test at 30° and 90° impact angles. Ductile erosion wear mechanism indicated by cutting and ploughing actions with number of lips, platelets and craters are observed on the damaged surfaces.

Figure 9 shows the highly deformed surfaces of SAE 208 steel after erosion tests 30° and 90° impact angles. Microcutting marks along with number of lips, platelets and craters formed due to the plastic deformation of the steel are clearly visible in the SEM micrographs. Figure 9(b) clearly shows the formation of lips, platelets and craters due to the severe plastic deformation of the steel at 90° impact angle suggesting the ductile behaviour of the SAE 208 steel.

Figure 10 shows the surface SEM micrographs of IS2062 structural steel eroded at 30° and 90° impact angles. Higher ploughing and cutting action marks with plastically deformed surfaces suggest the ductile mode of erosion mechanism for the IS 2062 structural steel.
3.2. Erosion wear of SAE213-T12, SAE213-T91, SAE 208 boiler steels and IS 2062 structural steel at 400 °C temperature

3.2.1. Visual examination
Figure 11 shows the macrographs depicting the erosion scars of SAE 213-T12, SAE 213-T91, SAE 208 boiler steel and IS2062 structural steel eroded at 400 °C temperature, at the impact angles of 30° and 90°. The main difference between the room temperature and 400 °C temperature is erosion wear scar depths at both the angles. At 400 °C temperature, steel materials became soft and more ductile, which can easily deform during the continuous impact of erodent particles.

3.2.2. Erosion behaviour of different steels at 400 °C temperature
The erosion rates (g g⁻¹) against cumulative mass of erodent for the steel samples subjected to erosion at 400 °C temperature, at an impact velocity of 42.3 ms⁻¹ and impact angles of 30° and 90° have been compiled in figures 12 and 13 respectively. The variation in erosion rate of IS2062 structural steel at 400 °C was more during the initial cycles irrespective of the impact angle. Comparatively higher variation in erosion rates have been observed through-out the erosion tests at 400 °C for both 30° and 90° impact angles, in the cases of boiler steels. This might be due to the initiation of oxidation of boiler steels at 400 °C temperature. The other reason for this behaviour may be a result of irregular interactions between strain hardening and embrittlement at various stages of erosion test. From the figure 14, it is clear that SAE213-T91 boiler steel has shown lowest erosion rate at 30° impact angle and SAE213-T12 boiler steel has given lowest erosion rate at 90° impact angle. The difference in steady state erosion rates of SAE213-T91 boiler steel at 30° and 90° impact angles is comparatively less than the other steels. The higher steady state erosion rates at 30° impact angle than that at 90° impact angle for all the steels clearly indicate the ductile mode of erosion behaviour. The higher erosion rate of IS2062 structural steel as compared to...
other steels at both the impact angles may be due to the lower hardness of IS2062 structural steel. At 400 °C temperature, the hardness of SAE213 T12 and SAE213 T91 boiler steel is going to be reduced due to heating i.e. the erosion resistance of these boiler steel is not much high as comparison to room temperature.

3.2.3. Morphological examination

Figures 15–18 show the SEM micrographs of the eroded surfaces of all the steels at 400 °C. SEM micrographs of all the steels clearly depict the plastically deformed surfaces with lips, platelets and craters formed along with some microcutting marks at 400 °C temperature. SEM micrographs at 400 °C temperature have shown more
Figure 12. Erosion rate (g g$^{-1}$) against cumulative mass of erodent for the steel samples subjected to erosion at 30° impact angle and at 400 °C temperature.

Figure 13. Erosion rate (g g$^{-1}$) against cumulative mass of erodent for the steel samples subjected to erosion at 90° impact angle and at 400 °C temperature.

Figure 14. A histogram illustrating the steady-state erosion rate of different graded boiler and structural steel at 30° and 90° impact angles at 400 °C.
ploughing and deformation actions as compared to that at room temperature indicating the increase in ductility of steels at 400 °C temperature. Higher ductility of target material provides relief from high velocity particles by partially consuming their kinetic energy and in permitting localized deformation at impact sites, thus minimizing the chances of cracking. It has been reported in the literature that the yield strength of all the steels reduces with the increase in temperature\[21\]. The drop in hardness with temperature occurs even more rapidly. Since the decrease in the hardness and the strength of these steels with temperature lead to increased penetration of impacting particles causing surface damage, enhanced subcritical crack growth, etc This leads to reduction in erosion resistance of steels at high temperature, as observed from figures 15–18.

4. Conclusions

Based on the erosion experiments carried out on boiler steels, following conclusions are drawn:

- SAE213-T12 and SAE213-T91 boiler steels have shown comparatively better erosion resistance at 30° and 90° impact angles than other two steel. Further, SAE 208 steel and IS2062 structural steel exhibited a very similar performance under erosion environment.
- In all the cases, the erosion rates at 30° impact angle was found comparatively higher than that at 90° impact angle, thus indicating the ductile behaviour of all the tested boiler steels at room temperature and 400 °C.
- SAE213-T91 boiler steel has shown better erosion performance in all tested condition at both room temperature and 400 °C temperature except 90° impact angle and 400 °C temperature where SAE213-T12 boiler steel has shown better erosion resistance than others.
Figure 16. SEM micrographs of the eroded surfaces of SAE213-T91 boiler steel at 400 °C (a) at 30° impact angle and (b) at 90° impact angle.

Figure 17. SEM micrographs of the eroded surfaces of SAE208 steel at 400 °C. (a) at 30° impact angle and (b) at 90° impact angle.
High hardness material such as SAE213-T91 and SAE213-T12 boiler steel have given better erosion results due to presence of high Cr content.

Erosion takes place through plastic deformation of material along with the formation of craters and lips at 90° impact angle. The eroded samples at 30° impact angle have shown that the material removal occurs by the cutting, ploughing and plastic deformation.

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ORCID iDs

Prashant Kumar Singh  
https://orcid.org/0000-0002-0580-4863

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Figure 18. SEM micrographs of the eroded surfaces of IS2062 structural steel at 400 °C. (a) at 30° impact angle and (b) at 90° impact angle.
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