ABSTRACT

Materials played key role in the development of society. As the industrial requirements are increasing day by day it become necessary to build up new materials or to amend the existing materials to meet these necessities. In past, significant advancement has been made in utilizing materials depending upon their experimental information related to properties and performance and succeeding treatment. Advancements of basic understanding and the capacity to design material prosperity to demanding requirements are most clear in advanced materials.

Erosion is a matter of significant industrial importance, though erosion is studied broadly by researchers but it received little consideration from the metallurgists. Earlier studies were restrained to investigations of the mechanical and physical processes or experimental determination of the relative erosion resistance of materials without studying the nature of damage that results in erosion of materials. Solid particle erosion is affecting boilers in power generation and fertilizer industry. The causes of repeated boiler tube failures are diagnosed as erosion and corrosion. The boiler tubes surface got eroded by the flue gas which passes through the tubes, leads to premature failure of boiler tubes due to reduction of wall thickness mainly at the side of the tubes.

In solid particle erosion the contact duration between erodent and target material is temporary as compared to abrasive wear, sliding wear, machining and grinding. The premature failure of the boiler tubes is due to localized prolonged overheating and erosion. The ash content of Indian coal is 50%, this ash contains 15% abrasive material like hard quartz which is highly abrasive and increases the erosion propensity of coal, as a consequence large variety of engineering industries mainly fertilizers and power generation industries faces premature failure of boiler components. So it is very important to forecast the erosion rate of components in case of coal-fired boiler industries. The causes of boiler tube failure are reported as, 30% in superheater, 15% in re heater, 40% in water wall tubes, 5% in cyclotron and 10% in economizer. Erosion-corrosion is acknowledged as 50-75% downtime of power-generating plants. The fly ash erosion decreases the tube wall thickness to 85-95% which is of (0.8-0.3) mm wall thickness. In worldwide energy sector 37% of electrical energy is generated by burning of coal, to increase availability of electricity the power plants should generate effectively without failure.
The present research is concentrated on investigation of solid particle erosion behavior of boiler tube materials and characterization of various erosion mechanisms responsible for the degradation of materials and premature failure of boiler parts. The research work was started with the study of boilers which are in operation at National Fertilizers Limited Naya Nangal (Punjab) India. The steam generation plant has three boilers and they face frequent boiler tube failures result in unplanned shut down of plant and production loss. The job history cards were studied and parts facing repeated failures were identified. During investigation it was observed that bank tubes and economizer tubes faced repeated failure. The bank tubes are made of SA192 steel and economizer tubes are made of SA210GrA1 steel. The detail study of the boiler tube materials composition, dimensions and mechanical properties was done. The failure analysis of water wall tubes and economizer tubes were carried out. It was observed that solid particle erosion is primarily responsible for boiler tube failure by reducing the wall thickness. The fly ash in combustible flame eroded the sides of the boiler tube. The tube thickness was measured at failure point and wall thickness was reduced significantly. The coal sample was collected from National Fertilizers Limited Naya Nangal and tested in the laboratory. The result reflected high ash content of 47.95 % which is responsible for boiler tube failure due to erosion. The scanning electron microscope images of fly ash were captured to analyze the particle size and shape. The image reflected that the size of ash particle varies from 20 to 50µm and mixture of round and sharp corner particles. This fly ash in combustible flame triggers the erosion rate.

So to investigate material loss, erosion behavior and erosion mechanisms involved in solid particle erosion, the actual experimentation was conducted under same boiler operating conditions. The steel samples of 25mm x 25mm x 5 mm dimension of SA192 and SA210 GrA1 boiler steels were prepared from boiler tubes for erosion investigation and characterization. The erosion behavior of the steel samples was experimentally investigated at room temperature and at high temperature that simulate the boiler operating conditions. Erosion test was performed by using Ducom Instruments’ air jet erosion test rig TR-471-M10, which is able to conduct erosion test at ambient temperature and high temperature. The impingement angles were varied as 30°, 45°, 60° and 90°. The velocity of air jet containing erodent particle was maintained at 35 m/s. Each sample was tested for three hours duration. The erosion test was performed in three steps.
In first step the erosion tests were conducted on steel samples, under ambient temperature, in which the steel sample and air jet was maintained at 25°C. The impact angles of air jet were varied as 30°, 45°, 60° and 90°. In second step the erosion tests were carried out at high temperature, in which steel samples were heated to 600°C and air jet was maintained at 800°C. The impact angles of air jet were varied as 30°, 45°, 60° and 90°. In third step the erosion tests were performed on friction stir processed steel samples at high temperature. In which steel samples were heated to 600°C and air jet was maintained at 800°C. The impact angles of air jet were varied as 30°, 45°, 60° and 90°. This experiment was conducted with the aim to compare the results at high temperature erosion test to estimate the scope of material protection due to friction stir process.

After the erosion test the macroscopic and microscopic examination were done on eroded steel samples. The macroscopic examination included visual inspection, material loss calculations and surface roughness degradation due to erosion. The microscopic examination included optical microstructure examination, SEM, XRD, EDS and EBSD examination.

The optical micrographs were captured for visual inspection of the eroded test samples. The optical micrographs showed scar on the surface exposed to the erosion. The elliptical scar was generated on the test sample at 30° impact angle, which cover the largest area among all impact angles. Deep oval scar was observed at 45° impact angle. Small circular scar was observed at 60° impact angles. At 90° impact angle confined circular scar was observed which covered smallest area among all impact angles. The erosion test at ambient temperature showed no sign of oxidation. The effect of oxidation and erosion-corrosion were observed at high temperature erosion test.

The weight of each sample was measured before and after the erosion test to calculate material loss. The material loss was small at 30° impact angle; it started increasing with increase in angle. Maximum material loss was observed at 45° impact angle. With further increase in impact angle to 60° material loss start decreasing. Minimum material loss was observed at 90° impact angle. At ambient temperature erosion test, maximum material loss was recorded of 0.0075 grams at 45° impact angle for SA192 steel and 0.0046 grams at 45° impact angle for SA210GrA1 steel. At high temperature erosion test, maximum material loss was recorded of 0.0415 grams at 45° impact angle for SA192 steel and 0.0184 grams at 45° impact angle for
SA210GrA1 steel. This has reflected that with the rise in temperature the mass loss has been increased by 4.5 times for SA192 steel and 3 times for SA210 GrA1 steel. It has reflected that SA210GrA1 steel showed better erosion resistance to solid particle erosion as compared to SA192 steel.

Surface roughness examination was conducted on each sample by measuring the surface roughness before and after the erosion test, it has estimated the surface roughness degradation due to erosion. The results reflected that at ambient temperature erosion test, maximum surface roughness degradation occurred at 45° impact angle for both steel samples. The surface roughness degradation of 2.55µm occurred at 45° impact angle for SA192 steel and 2.51µm occurred at 45° impact angle for SA210GrA1 steel. At high temperature erosion test, maximum surface roughness degradation occurred at 45° impact angle for both steel samples. The surface roughness degradation of 1.24µm occurred at 45° impact angle for SA192 steel and 3.38µm occurred at 45° impact angle for SA210GrA1 steel.

Microscopic examination was done on scanning electron microscopic images. The SEM image of erosion test conducted on SA192 steel at ambient temperature reflected small craters and impressions of micro cutting at 30° impact angle. The ploughing effect of erodent particle created big deep craters at 45° impact angle. Hills formation observed at 60° impact angle. Small craters with lip formation appeared at 90° impact angle. The SEM micrographs of erosion test conducted at ambient temperature on SA210GrA1 steel showed small craters and impressions of micro cutting at 30° impact angle, deep craters with lip formation occurred at 45° impact angle. Hills formation with small craters appeared at 60° impact angle. Due to striking of erodent particle at 90° impact angle small craters spread over the surface and hills formation occurred. At high temperature erosion test oxidation erosion was clearly observed in case of both steel samples. The SEM micographs of erosion test conducted at high temperature on SA192 steel reflected wide craters and layer formation at 30° impact angle. Deep craters and hills formation observed caused by ploughing effect of erodent particle at 45° impact angle. The layer formation observed at 60° impact angle. At 90° impact angle small craters appeared and erodent particles got entrapped in the cavities. The SEM micrographs of erosion test conducted at high temperature on SA210GrA1 steel showed small craters, hills formation at 30° impact angle, deep craters appeared at 45° impact angle due to
ploughing effect of erodent particle, chip formation at 60° impact angle and undercuts and micro cutting with squeezing action were appeared at 90° impact angle

The scratching and ploughing due to rubbing of erodent has been identified as material removal mechanism at 30° impact angle. The ploughing generated cracks and cuts at 45° impact angle. The forging and pitting has been observed at 60° impact angle. The adhesion and sputtering observed at 90° impact angle. Ductile mode of material removal was appeared due to ploughing effect at oblique angle, which primarily has been responsible for maximum material removal at 45° impact angle in both steel samples. Due to pitting effect of erodent particle striking at 90° impact angle minimum material removal occurred. Electron diffraction spectroscopy examination reflected maximum concentration of iron, small concentration of iron oxide i.e. (sign of oxidation erosion) and some concentration of aluminium oxide i.e. (alumina powder entrapped in cavities) at high temperature erosion test.

The electron back scatter diffraction examination reflected that the average grain size diameter of SA192 steel sample is 43.9µm and that of SA210GrA1 steel is 16µm, this indicated that SA210GrA1 steel has more refined grains as compared to SA192 steel. The more hardness of surface of SA210GrA1 steel is based on Hall-Petch equation. As per this equation, the hardness (H) is inversely proportional to the square root of the average grain size diameter ($d^{1/2}$). So, the SA210GrA1 steel showed better erosion resistance to solid particle erosion as compared to SA192 steel.

EBSD examination gave the reason to conduct third experiment on friction stir processed steel samples at high temperature. The friction stir process is a new technique to refine and modify microstructures of a material by the application of high strain rate deformation. After FSP the SA192 and SA210GrA1 steel samples were tested at high temperature conditions mentioned in second experiment. The results reflected that surface hardness of SA192 steel has been increased by 74% and the surface hardness of SA210GrA1 steel has been increased by 44% due to FSP. Friction stir process has increased resistance against solid particle erosion of SA192 and SA210GrA1 steels at high temperature from 50% to 70% depending upon the impact angle. The grain size has significant effect on metallurgical properties of material which has been illustrated by using FSP process. FSP is the economical process in comparison to other surface modification methods for providing better erosion resistant to boiler steel for high temperature applications.