In this chapter the results of erosion test conducted at ambient temperature, high temperature are discussed. The macroscopic and microscopic examinations are compared. The results are compared for friction stir processed steel samples at high temperature conditions for both steels to estimate the extent of protection it can provide against solid particle erosion for high temperature applications. The detailed discussions are explained in the forthcoming sections.

8.1 RESULTS AND DISCUSSIONS

8.1.1 Erosion Study At Ambient Temperature

In first phase experimentation was done at ambient temperature in which steel samples and air jet containing erodent was maintained at 25°C temperature. The results are discussed below.

8.1.1.1 Visual inspection

The erosion tests were conducted on SA192 and SA210GrA1 steel samples at 30°, 45°, 60° and 90° impact angles. At 30° impingement angle erosion scar is elliptical in shape and covered largest area among all impact angles for both steel samples. The scar produced at 45° impact angle is deep and oval in shape for both steel samples. The scar produced at 60° impact angle is circular in shape and covered half area in comparison to 30° impingement angle. At 90° impingement angle, small circular confined scar was produced which covered smallest area among all impact angles for both steels samples. More area was eroded due to oblige impact of erodent particle and ductile mode of material removal occurred at 30° and 45° impact angles. Due to normal impact of erodent particle small confined area was produced at 60° and 90° impact angles. The sputtering and pitting effect of erodent particle caused adiabatic shear band inducted spallation.
8.1.1.2 Mass loss analysis

The mass loss examination reflected that 0.0035 grams material is removed at 30° impact angle under ambient temperature conditions for SA192 steel and it increased to 0.0075 grams at 45° impact angle. The mass loss was decreased to 0.0023 grams at 60° impact angle. Minimum mass loss was observed at 90° impact angle of 0.0020 grams. The mass loss analysis showed that at oblique angle maximum material is removed due to ploughing effect of striking erodent particle at steep angle. Minimum material was removed at 90° impact angle which is due to pitting effect of striking erodent particle at normal angle in comparison to ploughing effect at steep angle and has been validated by [3]. In case of SA210GrA1 steel 0.0043 grams, 0.0046 grams, 0.0025 grams and 0.0015 grams material was removed at 30°, 45°, 60° and 90° impact angles respectively. The variation in material loss at oblique angle is mainly due to ploughing effect of erodent particle and at normal angle the pitting effect of erodent particle is responsible for minimum mass loss.

The SA210GrA1 steel showed better erosion resistance in comparison to SA192 steel due to refined grain structure.

8.1.1.3 Surface roughness degradation

The surface roughness degradation indicated the roughing of upper surface targeted by erodent. Figure 8.1 illustrated the surface roughness degradation of SA192 steel samples eroded at ambient temperature. The results indicated that for SA192 steel the average surface value of 0.26µm, 2.55 µm, 0.85µm and 0.68µm was reduced at 30°, 45°, 60° and 90° impact angles respectively. The maximum surface roughness degradation occurred at 45° impact angle which has been validated from maximum mass loss at same impact angle. Figure 8.2 illustrated the surface roughness degradation of SA210GrA1 steel samples eroded at ambient temperature. For SA210GrA1 steel 1.17µm, 2.51µm, 0.82µm and 0.44µm was reduced at 30°, 45°, 60° and 90° impact angles respectively. More surface roughness degradation occurred at oblique angles as compared to normal angles for both steel due to ploughing effect of erodent particle at oblique angles in comparison to pitting effect at normal angles.
The SEM analysis of SA192 boiler steel reflected that craters, lip formation appeared at oblique impact angles because of ploughing of erodent particle on the target surface and ductile material elimination mode was experienced. Near normal impact angle, due to pitting of erodent particle micro cutting and hills formation were
observed and material removal occurred with sputtering effect. In case of SA210GrA1 steel the craters appeared at 30º and 45º impact angles and micro cutting generated lip formation at many places which occurred due to scratching of erodent at steel angle. At 60º and 90º impact angles the craters are deep but small in size due to normal impact of erodent.

8.1.2 Erosion Study At High Temperature

In second phase experimentation was done at high temperature conditions in which steel samples were heated to 600ºC and air jet containing erodent was maintained at 800ºC temperature. The results are discussed below.

8.1.2.1 Visual inspection

The erosion test was carried out at high temperature to stipulate the actual working conditions of boiler. The optical macrographs were analyzed for visual inspection. This reflected that the erosion scar produced on the surface is small at the start and then start propagating towards the ends of the specimen. At 30º impingement angle erosion scar is elliptical in shape and covered largest area among all impact angles in both steel samples. Deep oval shaped scar is generated at 45º impact angle. The large scar is due to oblique impact of erodent particle at these angles. The scar produced at 60º and 90º impact angle are of confined circular shape this is due to normal impact of erodent particle in case of both steel samples. The erosion corrosion at high temperature is clearly illustrated in visual examination for both steel samples.

8.1.2.2 Mass loss analysis

The mass loss examination is significant in deciding the life of boiler tube. The mass loss for both steel samples has been calculated for continuous three hours under high temperature erosion at 30º, 45º, 60º and 90º impact angle. The mass loss for SA192 steel samples are 0.0317grams, 0.0415grams, 0.0130grams and 0.0019grams at 30º, 45º, 60º and 90º impact angles respectively. The mass loss for
SA210GrA1 steel samples are 0.0100 grams, 0.0184 grams, 0.0090 grams and 0.0024 grams at 30°, 45°, 60° and 90° impact angles respectively. The mass loss analysis indicated that temperature is very significant factor in solid particle erosion this has been illustrated in mass loss examination. Figure 8.3 shows comparison of mass loss for SA192 steel sample at ambient temperature and high temperature. The increase in temperature from ambient to high temperature condition has increased the mass loss by 4.5 times for SA192 steel depending upon the impingement angle. Figure 8.4 shows comparison of mass loss for SA210GrA1 steel sample at ambient temperature and high temperature. The increase in temperature from ambient to high temperature condition has increased the mass loss by 3 times for SA210 GrA1 steel depending upon the impingement angle. Maximum material is removed at 45° angle for both steel samples. As the angle is further increased, the material loss starts decreasing, which is due to pitting effect near normal angles as compared to ploughing effect of striking erodent particle at oblique angle. This reflected that material removal increases with angle up to 45° impact angle and start decreasing. The mass loss examination indicated that high temperature working environment of boiler trigger the erosion rate, which is highly responsible for untimely failure of boiler tubes due to decrease of tube wall thickness.
Figure 8.3 Comparison of mass loss for SA192 steel at ambient temperature and high temperature.

Figure 8.4 Comparison of mass loss for SA210GrA1 steel at ambient temperature and high temperature.

8.1.2.3 Surface roughness degradation

Figure 8.5 showed surface roughness degradation of SA192 steel samples eroded at high temperature. The surface roughness degradation occurred for SA192
steel sample was 0.91µm, 1.24µm, 1.06µm and 0.13µm at 30°, 45°, 60° and 90° impact angles respectively. Figure 8.6 showed surface roughness degradation of SA210GrA1 steel samples eroded at high temperature. The surface roughness degradation recorded for SA210GrA1 steel samples was 0.94µm, 3.38µm, 2.53µm and 2.93µm at 30°, 45°, 60° and 90° impact angles respectively. The surface roughness degradation analysis shows that impact angle is a highly influential factor for material removal and surface degradation. The failure of boiler tube starts with rubbing of upper surface with the impact of erodent in fly ash in combustible flame and propagated over the time. So to overcome this problem steel tube should be protected with coating materials or by some other techniques.

![Graph showing surface roughness degradation of SA192 steel samples eroded at high temperature](image)

Figure 8.5 Surface roughness degradation of SA192 steel samples eroded at high temperature
8.1.2.4 SEM analysis

The SEM micrographs gave complete information about eroded surface morphology. The micrographs are highly valuable for providing deep information about erosion mechanism involved in material removal in solid particle erosion. The SEM micrograph of both steel reflected that craters of moderate size appeared at 30° impact angle, big deep craters appeared at 45° impact angle, reflecting the ductile material removal mechanism due to ploughing of erodent particle. At 60° impact angle lip, chips and micro cutting impressions are illustrated. Hills formed at 90° impact angle. These are due to pitting of erodent particle.

The SEM micrographs reflected that the SA192 steel has deep craters as compared to SA210GrA1 steel. This indicated the better erosion resistance of SA210GrA1 steel. The results of mass loss and surface roughness degradation are also validated by SEM micrographs. The EDS spectra of SA192 and SA210GrA1 steel indicted the erosion oxidation of steel samples at high temperature conditions. The EDS spectra also indicated the presence of alumina erodent particle entrapped in craters. The better erosion resistance offered by SA210GrA1 steel was verified by EBSD analysis and described as per Hall Petch relation. As per this relation, the
surface hardness is inversely proportional related to the square root of average grain size diameter. Thus, the SA 210GrA1 steel showed better erosion resistance to solid particle erosion as compared to SA192 steel. The average grain size of SA192 steel was measured 43 microns while that of SA210GrA1 steel was 16 microns. The grain size measurement showed that the grains of SA210GrA1 are more refined. This has been illustrated in Figure 8.7 showing the comparison between grain size of SA192 and SA210GrA1 steel. The figure 8.7 illustrated that more refined grain steel provided better erosion resistance in comparison to large grain steel.
8.1.3 Erosion Study At High Temperature After FSP

The third phase experimentation was done on friction stir processed steel samples at high temperature conditions in which steel samples were heated to 600°C and air jet containing erodent was maintained at 800°C temperature. The results are discussed below.

8.1.3.1 Microstructure comparison

The optical micrographs were captured for both steel samples before and after friction stir process. Figure 8.8 showed grain refinement of SA192 steel sample due to friction stir process. Figure 8.9 showed grain refinement of SA210GrA1 steel sample due to friction stir process. As per Hall Petch equation the surface hardness of a material increases due to grain refinement, this has increased the erosion resistance of both steel at high temperature.
Figure 8.8 Optical micrographs of SA192 steel (a) before FSP (b) after FSP
8.1.3.2 Increase in surface hardness

The surface hardness was improved for both steels. The surface hardness was increased by 74% for SA192 steel and increased by 44% for SA210GrA1 steel. The
increase in surface hardness is attributed to friction stir process. The comparison is illustrated in Figure 8.10.

![Surface hardness in BHN of SA192 and SA210GrA1 steel before and after FSP](image)

**Figure 8.10** Surface hardness in BHN of SA192 and SA210GrA1 steel before and after FSP

### 8.1.3.3 Mass loss examination

The mass loss examination revealed that friction stir process provided protection against solid particle erosion by saving material loss at high temperature for both boiler steels. In case of SA192 steel 0.0207 gm material was saved at 30° impact angle, 0.0266 gm material was saved at 45° impact angle, 0.0087 gm material was saved at 60° impact angle and 0.0010 gm material was saved at 90° impact angle. In case of SA210GrA1 steel 0.0064 gm material was saved at 30° impact angle, 0.0116 gm material was saved at 45° impact angle, 0.0063 gm material was saved at 60° impact angle and 0.0017 gm material was saved at 90° impact angle. The FSP has been observed as new technique for the protection of boiler tubes at high temperature working conditions.

### 8.1.3.4 Surface roughness degradation

Figure 8.11 showed surface roughness degradation of friction stir processed SA192 steel samples eroded at high temperature. The surface roughness degradation occurred for SA192 steel sample was 0.15μm, 0.46μm, 0.26μm and 0.30μm at 30°, 45°, 60° and 90° impact angles respectively. Figure 8.12 showed surface roughness
degradation of friction stir processed SA210GrA1 steel samples eroded at high temperature. The surface roughness degradation recorded for SA210GrA1 steel samples was 0.46µm, 0.81µm, 0.44µm and 0.20µm at 30°, 45°, 60° and 90° impact angles respectively. The surface roughness degradation analysis showed that less surface roughness degradation occurred due to protection provided by friction stir process. This has also validated the material removal protection due to friction stir process. So friction stir process has protected the steel samples against solid particle erosion at high temperature.

Figure 8.11 Surface roughness degradation of friction stir processed SA192 steel samples eroded at high temperature
8.1.3.5 SEM examination

In the above discussions we observed the protection has been provided by friction stir process against solid particle erosion in terms of material removal and surface roughness degradation. The SEM images were compared for both steel samples at 45° impact angle conditions to see the surface morphology of eroded steel samples with and without friction stir process. Figure 8.13 showed that friction stir process provided protection to SA192 steel sample against erosion at high temperature at 45° impact angle. Figure 8.14 showed that friction stir process provided protection to SA210GrA1 steel sample against erosion at high temperature at 45° impact angle.
Figure 8.13 FSP protected SA192 steel sample against erosion at high temperature

(a) Without FSP

(b) With FSP
So, friction stir process may be adopted to protect the boiler tubes which are under high temperature working conditions and facing solid particle erosion in the form of fly ash in combustible flame. With the application of this technique the life of boiler tubes will enhance and sudden boiler tube failures may be prevented to overcome the premature breakdown of the plants.