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EXPERIMENTAL STUDIES ON THE EROSION RATE OF LOW CARBON STEEL BANK TUBES OF PROCESS BOILERS IN STRAIN-HARDENED AND SUB- CRITICAL ANNEALED CONDITION

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ABSTRACT

Erosion of bank tubes in bi-drum boilers is one of the critical factors leading to the shutdown of power plants. It has been found that more than 25% of all boiler tube failures worldwide are caused by fly ash erosion. Previous studies have established that the major factors influencing the fly ash erosion process are the velocity, impact angle, feed rate and particle size of fly ash. In the present study, the effect of heat treatment conforming to ASME code, during fabrication of bank assembly carbon steel tube conforming to specification ASME SA-192, on erosion rate is analyzed taking into account the factors of velocity, impingement angle, feed rate and particle size of fly ash. Considering the fabrication of the SA-192 tubes which involves cold bending of tubes which in turn leads to strain hardening, bent-tubes with sub- critical annealed condition and bent-tubes without sub- critical annealing condition have been studied. The experiments were conducted in the air jet erosion test rig at M/s. Bharat Heavy Electricals Limited, Tiruchirappalli, India. It has been found that during fabrication of the tubes, bent-tube with sub -critical annealing when compared to bent-tube without sub- critical annealing condition has less erosion rate for all velocities, impact angles, feed rates and different particle sizes of fly ash. This characteristics in bent-tube with sub -critical annealing emerges due to the higher ductility of these tubes compared to the tubes which were not sub- critically annealed.

Keywords: Bank tube, Fly ash; Strain hardening; Sub critical Annealing; tube erosion.

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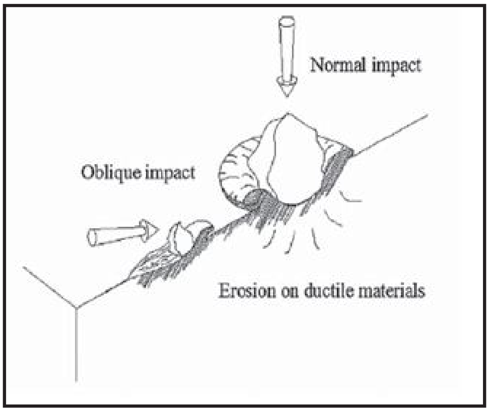
INTRODUCTION

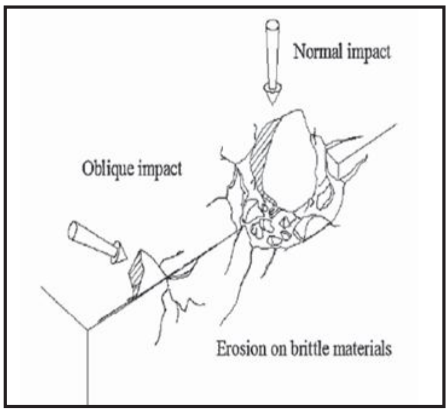
Solid particle erosion may be defined as the removal of material from the surface by the repeated impact of hard and angular particles travelling at considerable velocities. The erosion of metallic tubes in tube banks by particles suspended in gas flows is a serious problem in chemical plants, coal combustion equipment and process when operated in contaminated environments. The damaging effect of erosion substantially reduces the useful life of the tubes. Various ferrous and non-ferrous materials are extensively used in erosive wear situations. Hence, solid particle erosion of surface has received considerable attention in the past decades.

MATERIAL REMOVAL (EROSION) MODEL

The mechanical interaction is different for ductile and brittle materials. In the case of ductile materials the impacting particle cause severe, localised plastic strain which is more than the strain to failure of the deformed materials. For brittle materials, the force of erodent particles causes cracking and chipping off of micro-size pieces, known as micro cutting (Wang and Guoyang,2008). This difference is clearly shown in Figure 1 (a) & (b).



(a)



(b)

Fig. 1 (a) & (b): Erosion mechanisms in ductile and brittle material

For ductile material, the erosion mechanism involves sequential plastic deformation process of platelet formation and crater formation due to forging and extrusion. Platelets are initially extruded from shallow craters made by the impacting particle. Once formed, the platelets are forged into a strained condition, in which they are vulnerable to being knocked off the surface in one or several pieces. Owing to the high strain rates, adiabatic shear heating occurs in the surface region immediate to the impact site. Beneath the immediate surface region, a work hardened zone forms, as the kinetic energy of the impacting particles is enough to result in a considerably greater force being imparted to the metal than it is required to generate platelets at the surface. When the surface is completely converted to platelets and craters and the work-hardened zone reaches its stable hardness and thickness, steady state erosion begins. The reason why the steady state erosion rate is the highest is because the sub-surface cold-worked zone acts as an anvil, thereby increasing the efficiency of the impacting particles to extrude-forge platelets in the highly strained and most deformable surface region. This cross-section of material moves down through the metal as erosion loss occurs. In the platelet mechanism of erosion, there is a localised sequential extrusion and forging of metal in a ductile manner, leading to removal of the micro segments thus formed. During plastic deformation, the normal component of the particle's kinetic energy is used to extrude-forge the material.

Satyanathan (2001) showed that in M/s. Bharat Heavy Electricals Limited (BHEL) supplied boilers; the fly ash erosion is the major concern for almost one third of total tube failures. The major factors influencing the erosion process are the amount of ash particles, its velocity and the design conditions. Finnie *et al.* (1967) developed analytical model to find the erosion rate based on the assumption that the mechanism of erosion was due to micro-cutting. Later it was demonstrated by Levy (1981) that the micro-cutting was not the primary mechanism by which ductile structural metal erode. They conducted experiments and concluded that for ductile material the impacting particles cause severe localized plastic strain, which exceed the strain of material and cause the failure of deformed material, and for brittle materials the energy possessed by erodent particles cause cracking and removal as micro size pieces. Levy (1981) also demonstrated that in ductile materials, erosion rate is lower when its ductility is increased. Misra and Finnie (1981) explained that the number of particles actually striking the surface do not increase the erosion rate in the same way as the number of particles traveling towards the specimen due to the shielding effect provided by the rebounding particles. Levy (1982) tested the same material of specification with different micro structures like fine pearlite and coarse pearlite having different elongation percentage, and found that the erosion rate is less for the material having higher elongation percentage.

Liebhard and Levy (1991) had highlighted that the erosion rates for change in particle size are difficult to explain quantitatively because a number of factors like particle velocity and kinetic energy, number of particles striking the target, interference between the striking and rebounding particles, shape of the particles and the angle of impact of particles are involved. Mbabazi *et al.* (2004) had conducted erosion test on mild steel plate with three different fly ash samples from Lethabo, Matimba and Matla power plants in South Africa at different fly ash velocities and found that experimentally calibrated general model which yielded results that differed by less than 15% from the values measured experimentally. Oka *et al.* (2005a) had stated that material removal is caused by indentation process. It was found that degree of load relaxation depends upon the ability of plastic flow for soft materials. It was concluded that a predictive equation containing material hardness and load relaxation ratio which could be related to find experimental erosion damage data. Oka *et al.* (2005b) had expressed that the mechanical properties of the material can be regarded as the main parameter for estimating erosion damage. Desale *et al.* (2006) had expressed that the surface morphology of the specimen showed deep craters and higher value of average surface roughness for angular particles. Harsha *et al.* (2008) had conducted experiments for ferrous and nonferrous materials to find the erosion rate against the cumulative weight of impinging particles. It was observed that the erosion rate initially increases with increasing cumulative weight of impinging particles and then reaches a steady state value. Wang and Guoyang (2008) had demonstrated that for ductile materials the erosion is caused by the micro cutting and micro ploughing of the erodent particles. For brittle materials like ceramics, the energy transfers from erodent material to the specimen. This process induces the material deformation, crack initiation and propagation, and causes removal of material from the specimen surface. Kain *et al.* (2007) studied the failure of low carbon steel tubes considering the SA-210GrA-1 material.

Hutchings and Winter (1974) studied the mechanism of metal removal by impacting the metal targets at an oblique angle by metal balls at velocities up to 250 m/s. They suggested that the initial stage of metal removal is the formation of lip at the exit end of the crater by shearing of the surface layers. Above critical velocity, this lip is detached from the surface by the propagation of ruptures at the base of the lip.

Das *et al.* (2006) investigated the effect of temperature on the basis of the observation that the erosion rate at acute impingement angle increases significantly with temperature, suggesting that steel tends to show behaviour more typical of a ductile material at elevated temperatures. The yield stress (N/mm^2) and temperature (K) functionality has been derived through a polynomial approximation for various grades of steel on the basis of the available tensile property data. This model has been implemented in a user-interactive computer code (EROSIM-1) which embodies the solid particle erosion mechanism due to cutting wear and repeated plastic deformation. The overall erosion is estimated from the contributions of both the mechanisms of wear. Erosion behaviour at elevated temperatures has been incorporated through the derived functionality of the tensile property (yield stress) with temperature using appropriate modification of yield strength.

Sundararajan and Shewmon (1983) had proposed a correlation between the erosion rate and the thermo-physical properties of the target, for the erosion of metals by particles at normal incidence. This model employed a criterion of critical plastic strain to determine when the material will be removed. Their erosion model (localized model) predicted very well the experimentally observed erosion rates rather than the fatigue-type model.

Jennings *et al.* (1976) have derived mathematical models based on target melting and kinetic energy transfer for predicting ductile target erosion. Dimensional analysis was employed in the development of a mathematical model for predicting the erosion of ductile materials. The basis of the model was an identified erosion mechanism (target melting) and the model was verified in an erosion testing program using three stainless steels, two aluminium alloys, a beryllium copper alloy and a titanium alloy; the erosive agents were three dusts with hard angular particles and one dust with spherical particles.

Irma Hussainova *et al.* (1999) investigated the surface damage and material removal process during particle-wall collision of the solid particles and hard metal and cermets targets. Targets were impacted with particles over the range of impact velocities (7-50 m/s) at impact angle of 67°. The experimentally observed variations of the coefficient of velocity restitution as a function of the test material properties, impact velocity and hardness ratio were adequately explained by a theoretical model presented by them.

Levy and Foley (1983) studied the erosion behavior of different steel like a plain carbon steel (AISI-SAE 1020), an austenitic stainless steel (type 304) and a low alloy steel (AISI-SAE 4340). The testing was conducted at room temperature using aluminum oxide particles with an average size of 140 microns in an air stream. An attempt was made to characterize the erosion behavior as it relates to the mechanical properties obtainable in these alloys by conventional heat treatments. It was found that the ductility of the steels had a significant effect on their erosion resistance which increased with increasing ductility and that hardness, strength, fracture toughness and impact strength had little effect on erosion behavior.

Oflynn *et al.* (2001) created a model to predict the solid particle erosion rate of metals and its assessment using heat-treated steels. The model proposed that erosion rate is related to the product of toughness and uniform strain. Two steels (EN 24 and EN 42) were heat treated to form a total of 12 different microstructures, each having distinctly different mechanical behavior. Erosion tests were carried out at a combination of three impact velocities and three angles of particle impingement in a rotating disc accelerator erosion tester. Tensile tests were carried out on all the heat-treated steels over a range of temperatures from room temperature to 400°C. The model predictions were not satisfied by mechanical property measurements made at room temperature. However, for each given erosion test condition, a good linear relationship was found between room temperature erosion rate and high strain rate (toughness x uniform strain) when mechanical properties were measured at elevated temperatures. The elevated temperature chosen to give the best-fit was between 200° and 300°C depending on the impact velocity. It is believed that the significance of the elevated temperature property measurements is that they account for localized heating occurring at the impacting particle during the high strain/strain-rate deformation typical of erosion. Certain heat-treatments gave a poorer fit to the relationship and explanations for this are proffered.

EXPERIMENTAL SET-UP

The experimental set-up used for the present study is an air jet erosion test rig. The schematic diagram and the photographic view of air jet erosion test rig are shown in Figure 2. It is owned by Research and Development Lab of M/s. BHEL, Tiruchirappalli, India. The test rig is manufactured as per ASTM G76 standard.

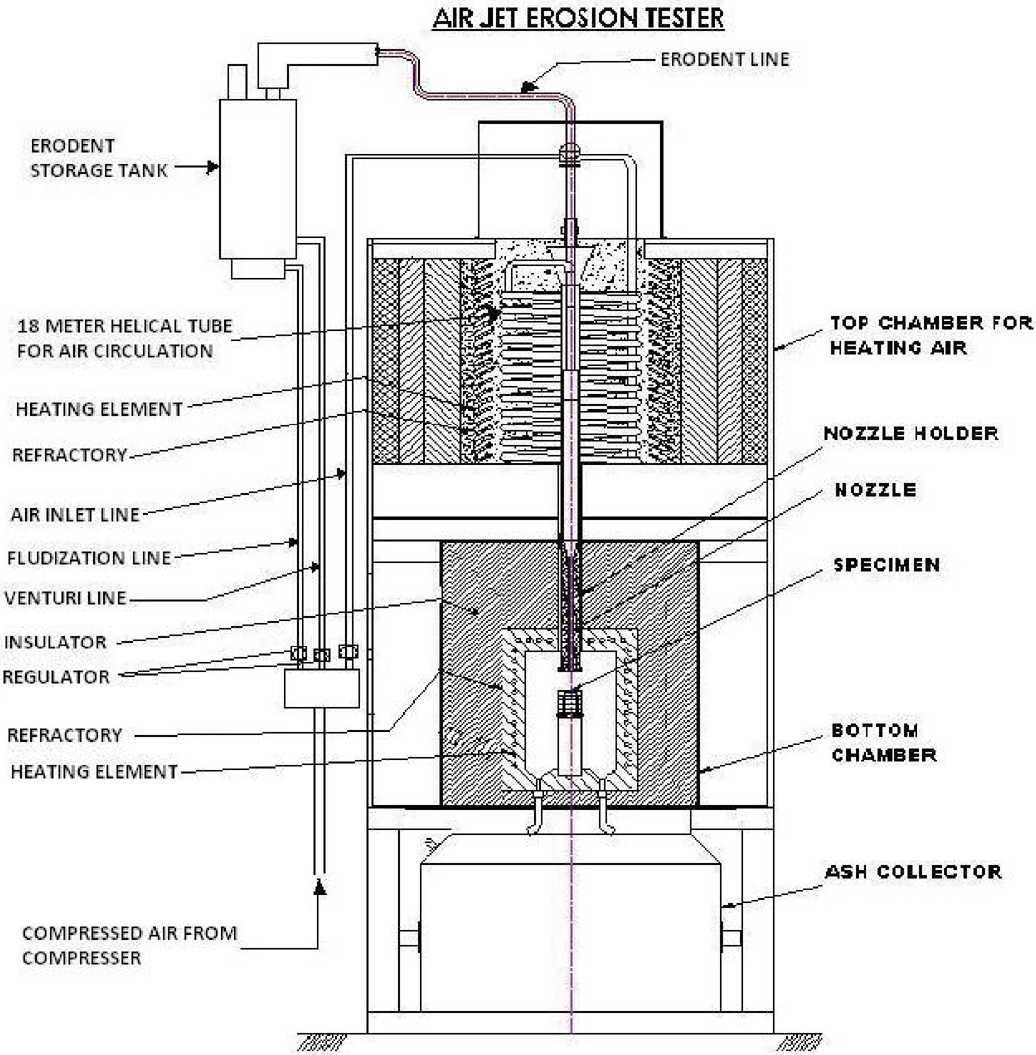


Figure 2: Schematic diagram of Air Jet Erosion Test Rig

EXPERIMENTAL PROCEDURE

In this study, tube samples of carbon steel tube material of SA-192 specification, currently in use for bank tubes in almost all power boilers are tested in required conditions at M/s. BHEL's laboratory (recognized by National Accreditation Board for testing and calibration of Laboratories). The tested mechanical properties of tubes of SA-192 materials are given in Tables. The test specimen was weighed initially and then it was fitted in the jet erosion test rig at a desired angle using specimen holders. The fly ash is taken in the chamber provided. The velocity and the concentration of fly ash particles are adjusted by controlling the flow of air quantity through the fluidization chamber. A jet of air with the fly ash particles pass through a nozzle and hit the surface of the sample at an angle chosen to place the sample. After doing the experiment for a scheduled time, the sample is removed and it is cleaned and weighed to measure the weight loss. The amount of ash used is also measured. The erosion rate is computed as the ratio of loss of weight in grams of test specimen to kilogram of ash particles impinging on the test specimen surface. The erosive rate was evaluated at different impingement angles ranging from 15° to 90°, and at four different velocities of 32.5, 35, 37.5 and 40 m/s.

RESULTS AND DISCUSSION

Erosion Study On Bent-Tube With And Without Sub-Critical Annealing (Strain Hardened Tube)

The low carbon steel tubes having specification SA-192 has to be bent in cold condition during the fabrication of bank tubes. Ductility of tubes reduces during the bending operation. The thickness of the tube used is 4.5 mm. As per the ASME standard, Heat treatment is mandatory for low carbon steel tubes if thickness exceeds 19mm. The thickness limitation stipulated in the code is given by permitting the stresses produced to the level of the yield stress of the material and it does not take into account the erosion property. In current practice, heat treatment is not carried out for the fabricated bank tubes. By suitable heat treatment of the bent-tubes of the bank tubes, the lost ductility that occurs during the cold bending operation of the tube can be improved and thereby the erosion rate can be reduced. Erosion study is carried out for the bent -tube with sub- critical annealing SA-192 (SC) and for the bent-tube without sub-critical annealing SA- 192 (SH) (strain hardened tube).

Effect of Velocity, Impingement Angle, Feed Rate, Particles Size and Temperature of Fly Ash Particles on Tube Erosion

Figure 3 shows erosion rate at room temperature and at high temperature (400°C) for bent-tube with sub- critical annealing SA-192 (SC) and without sub- critical annealing SA-192 (SH) (strain hardened tube) at different impingement velocities ranging from 32.5 m/s to 40 m/sec and at impingement angle of 30°. The data for graphs are obtained after the steady state of the erosion rate is reached. Erosion rate for the bent- tube without sub- critical annealing (strain hardened tube) is higher than that of bent-tube with sub critical annealing for a given velocity attributing to ductility and percentage elongation of the materials.

In ductile materials, when fly ash particles impinge with a velocity, at the impact point the particle loses a fraction of its kinetic energy to the target material for deformation of the surface and shear strains are induced in the target material. When the shear strain exceeds the elastic limit of the target material, the fly ash particles penetrate the surface of the target material and form platelets, which are removed in the subsequent impingement of the particles. Fly ash particles have sufficient level of strength and integrity to cause erosion in the velocity range used in the experiment. It is the kinetic energy of the fly ash particle that has the greatest effect on the erosion rate of the tubes. The kinetic energy of the fly ash particles is proportional to velocity, which causes increase in erosion rate when the velocity of the fly ash particles is increased. Being the ductility of the sub-critical annealed bent-tube is more, the plastic deformation is increased and hence the erosion rate is decreased. So the sub- critical annealed bent-tubes have less erosion rate.

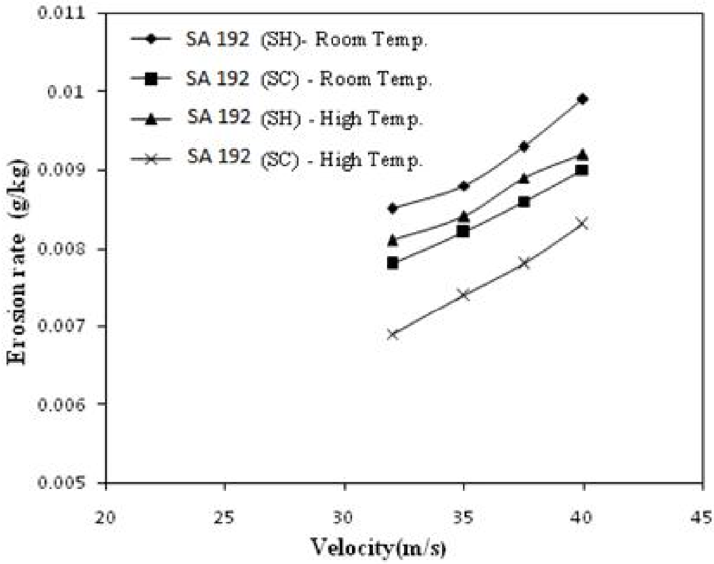


Figure 3: Effect of velocity of fly ash particles on tube erosion–SA-192 (SH&SC)

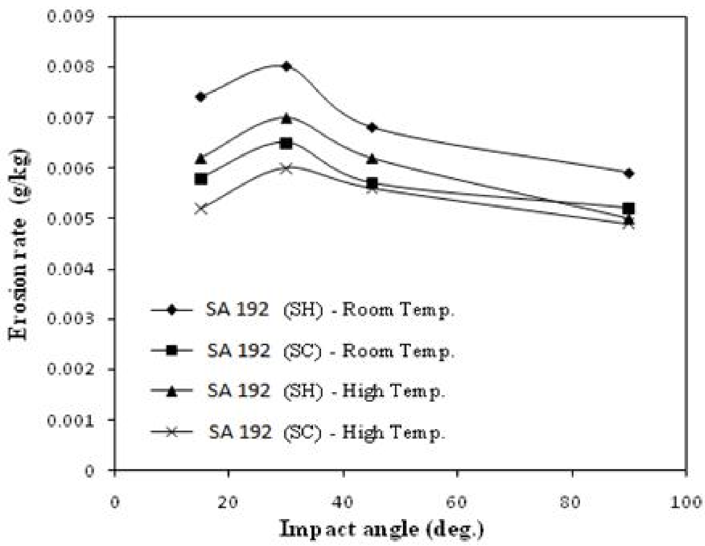


Figure 4: Effect of impingement angle on tube erosion SA-192(SH&SC)

Figure 4 shows the experimental results that are obtained by varying the impingement angles ranging from 15° to 90° at a velocity of 32.5 m/s at room temperature and at high temperature (400° C). The erosion rate increases with the increase in impingement angle initially then decreases with the increase in angle. At about an angle of 30°, the erosion rate is found to be maximum. This may be caused by the increase in depth of penetration of the fly ash particle in the target material when the impact angle is increased. When depth of penetration of the particle is increased, the plastic deformation in the target material is increased and thus the erosion rate is reduced. For the same fly ash particles and impingement angle, the erosion rate is mainly a function of target material properties.

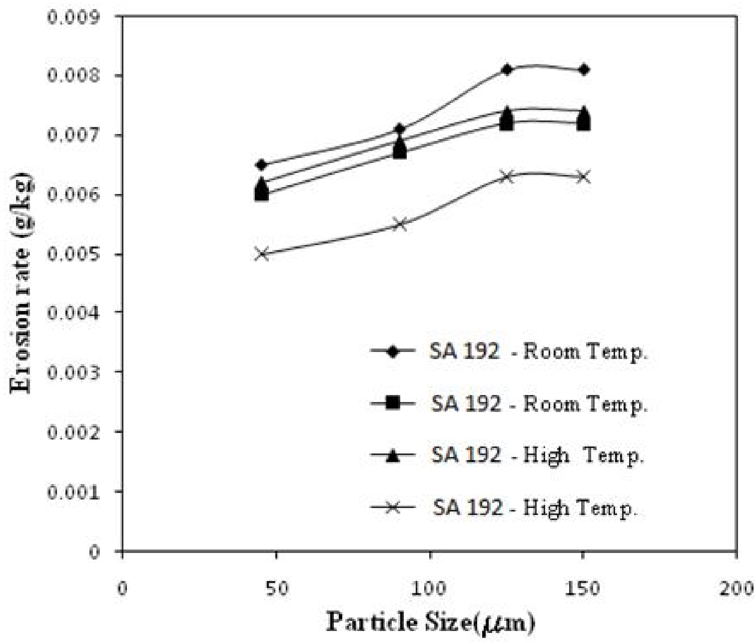


Figure 5: Effect of fly ash particles size on tube erosion SA-192 (SH&SC)

Figure 5 shows the erosion rate of the specimen for different particle size at room temperature and at high temperature (400° C) at a velocity of 32.5 m/s and at impingement angle of 30°. The erosion rate increases with the increase in particle size from 50 to 125 µm and beyond this size, there is no significant increase in erosion rate. More or less constant erosion rate with particle diameter above 125 µm is possible due to the combination of relation between the particle size, the number of particles striking the surface, its kinetic energy and the interference between incoming and rebounding particles. For particle sizes below 125 µm, the kinetic energy of the particles has to be low to be as effective in removing material as 125 µm size particles or more. When size of the particles are increased, the number of the particles actually striking the surface do not proportionally increase due to the shielding effect provided by the rebounding particles.

Figures 3, 4 and 5 also show that at high temperatures (400˚C), the erosion rate is decreased for both the conditions of the tube SA-192. This is due to the increase in ductility of the tube material SA-192 when temperature is increased.

Experiments are also conducted with four different feed rates of fly ash particles (2, 4, 6, and 8 g/min) with the constant velocity of 32.5 m/s and impingement angle of 30˚. The results are shown in Figure 6. In this experiment, the weight loss of the specimen is not calculated for per kg weight of fly ash particles as in previous experiments. Erosion rate decreases for the increase in feed rate of the fly ash particles. At higher feed rate of fly ash particles, there is particle-to-particle interference which reduces the effectiveness of the particle to erode the surface. Due to the particle-to-particle interference, the kinetic energy of the incoming particles gets reduced and there is a chance for some of the fly ash particles to get deflected by the rebounding particles from target. Figures 3, 4,5 and 6 shows that the erosion rate is less for the bent-tube with sub- critical annealing.

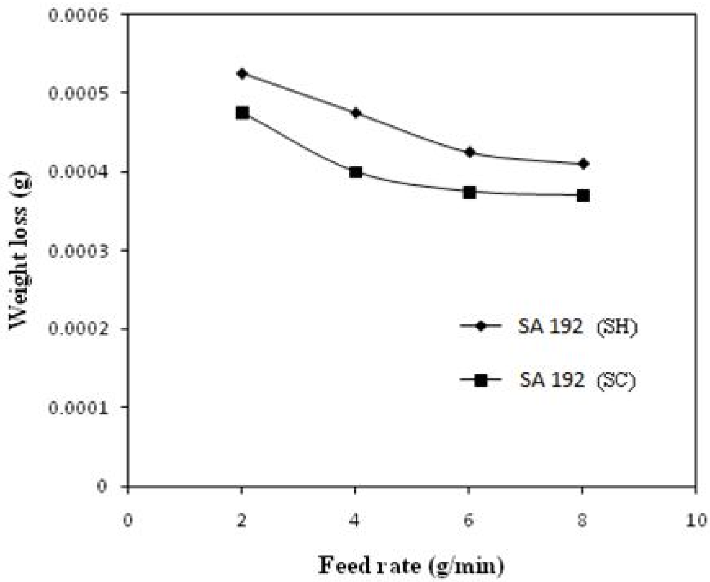
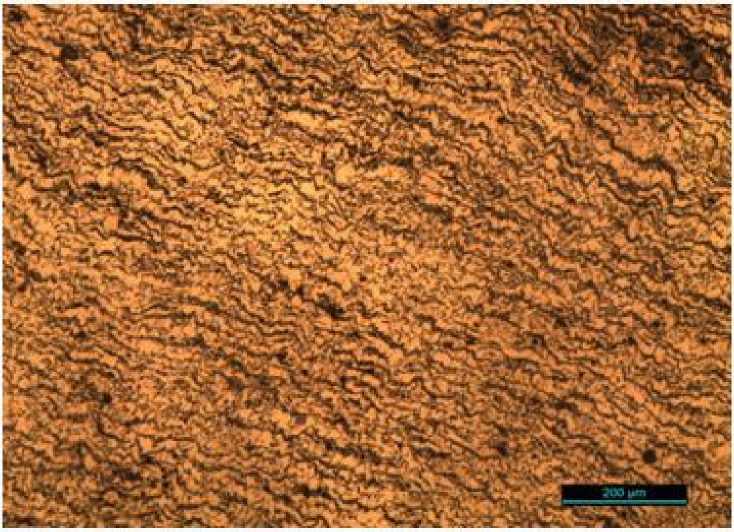


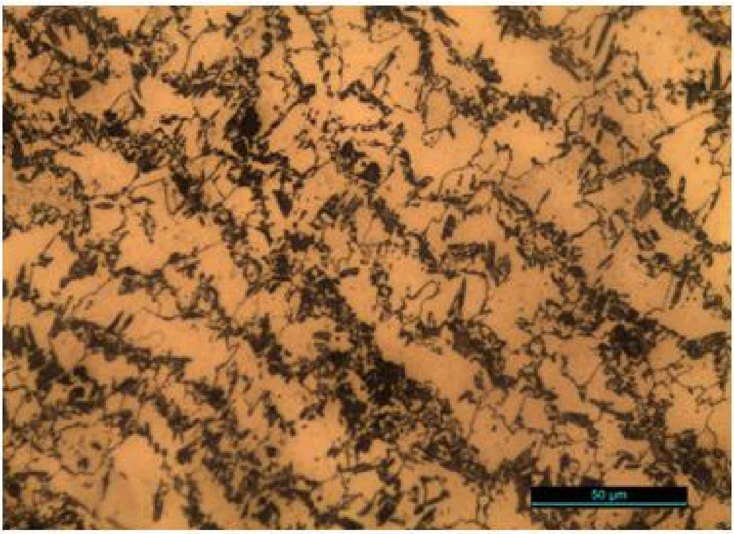
Figure 6: Effect of feed rate of fly ash particles on tube erosion SA-192 (SH&SC)

Microscopic Examination of Bent-tube with and without subcritical annealing

The samples of bent-tube without sub- critical annealing (strain hardened tube) and sub-critical annealed bent-tube are studied under microscope. The cross-sections of these samples are mounted, polished to diamond finish and etched in a 2% nital solution. The etched samples are examined under the microscope and the images are shown in Figures 7 & 8. Figure 7 shows the microscopic image of the bent-tube without sub- critical annealing (strain hardened tube). Cold working like bending results in strained and deformed crystal grains in bank tubes. The grains are elongated and hence deviate from the most stable equiaxial grains. On sub-critical annealing of bent strain hardened tube, recrystallisation forces come into play and elongated grains become equiaxial grains and regain its lost ductility to some extent. Figure 8 shows the structure of the tube after recrystallisation.

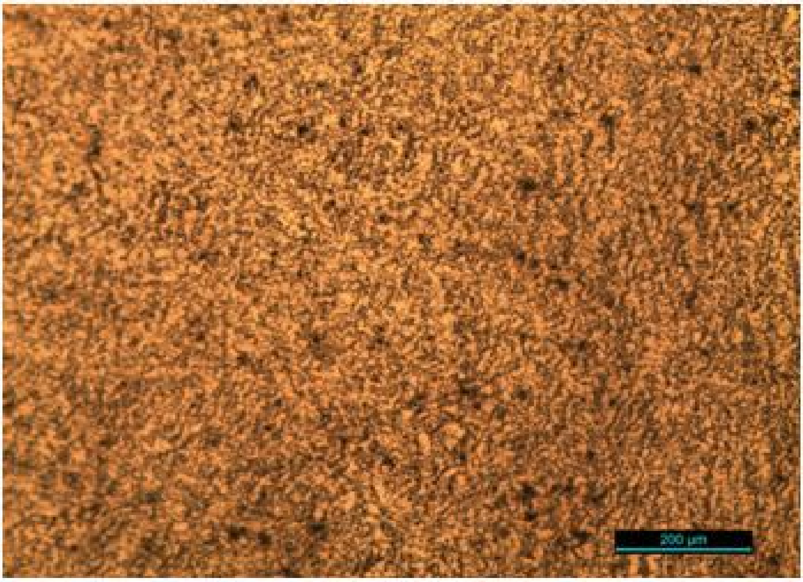


SA192 AT 100X ELONGATED GRAINS

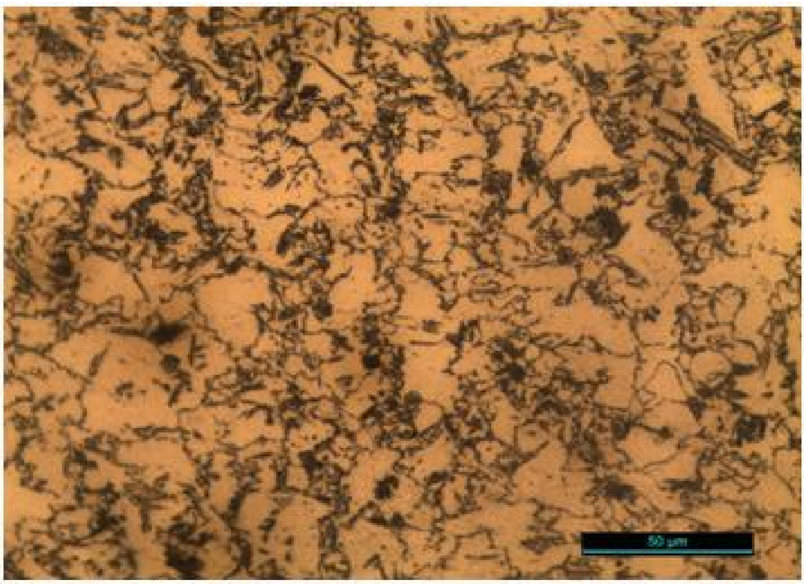


SA192 @ 500X ELONGATED GRAINS

Figure 7: Microscopic images of the bent-tube without sub- critical annealing (strain hardened tube)



SA192 AT 100X ELONGATED GRAINS



SA192 AT 500X EQUIAXED GRAINS

Figure 8: Microscopic images of the bent-tube with sub- critical annealing

Effect of Erosion Rate on Bent Tube with Sub-Critical Annealing

The erosion is greater in case of bent strain hardened tube. As the tube is bent, the ductility of the tube is lost due to the plastic deformation and the tube is strain hardened. Sub-critical annealing of the bent strain hardened tube (the tube is heated to 700° C i.e., just below its lower critical temperature and soaked there for half an hour and then cooled up to 400° C in furnace), allows work hardened grains in as-bent tube to re-crystallize and makes the tube to regain its lost ductility to some extent. As ductility is higher in sub-critical annealed bent- tube when compared to the bent-tube without sub-critical annealing (strain hardened tube), the erosion rate is less in sub-critical annealed bent-tube.

Scanning Electron Microscope Examination of Bent-tube

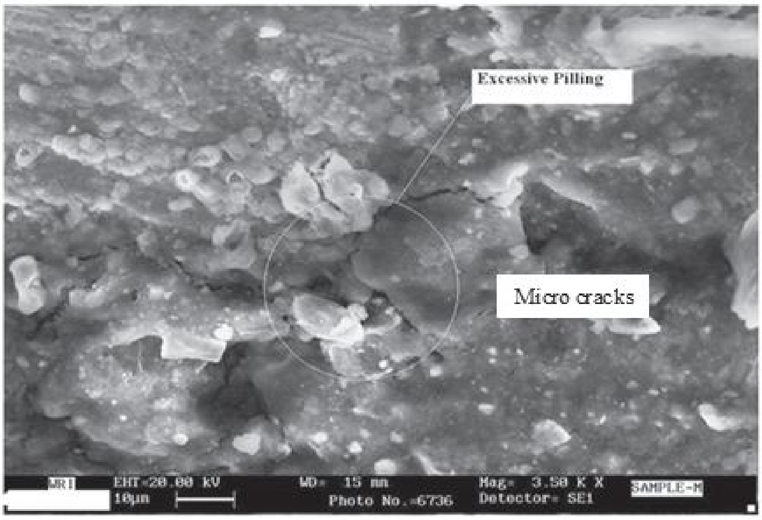


Fig.9: SEM images of the eroded specimen of the bent-tube

The sample is cut from the eroded area of the bent-tube. The sample is mounted, polished to diamond finish and etched in a 2% nital solution. The etched sample is examined under the Scanning electron microscope and the image is shown in Figure 9. The SEM image of the eroded area shows micro cracks which indicate the predominance of micro cutting wear mechanism in bent-tube as it become less ductile after the bending operation.

CONCLUSIONS

The following are the conclusions drawn from the present investigation:

- The selected low carbon steel tube conforming to ASME SA-192 is tested for mechanical properties like tensile strength, yield strength and percentage of elongation for all the selected heat treatment conditions in M/s. BHEL's Mechanical Test lab and found that the mechanical test results are in conformance with the values specified in ASME.

- The erosion rate of bent tube with sub- critical annealing is less compared to the bent tube without sub- critical annealing.
- The erosion rate of the tube decreases due to the predominance of platelet mechanism of erosion over micro cutting mechanism of erosion when ductility/percentage of elongation of the tube is increased.
- The study also confirmed that when the velocity of the fly ash particles is increased, the erosion rate also increases. When impingement angle of fly ash particles on the target is increased from 15° to 90°, the erosion rate is maximum at 30° and then decreases.
- The erosion rate increases with an increase in the fly ash particle size up to 125 μm and beyond that size there is no increase in erosion rate.
- The erosion rate is decreased at high temperature (400° C) due to the increase in ductility of the material at high temperature.

Thus, the paper indicates that by adopting heat treatment process mentioned above during fabrication, the ductility of SA-192 tube can be increased and thereby, the erosion rate can be decreased in bank tubes of bi-drum boilers.

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