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Materials

Experimental studies on the erosion rate of different heat treated carbon steel economiser tubes of power boilers by fly ash particles

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Abstract: The experimental investigations on the effect of the fly ash particle size, velocity, impingement angle, and feed rate were done with an emphasis on the effect of erosion on annealed SA 210 GrA1 (A) and normalized SA 210 GrA1 (N) carbon steel economizer-tube materials. Erosion rates were evaluated with different impingement angles ranging from 15° to 90°, at four different velocities of 32.5, 35, 37.5, and 40 m/s, and at four different feed rates of fly ash particles of 2, 4, 6 and 8 g/min. The erodent used was fly ash particles, sizes ranging from 50-250 μm of irregular shapes. Erosion rate is found to be the maximum at the impingement angle of 30°. Erosion rates of the carbon steel tube in different heat treatment conditions, annealed and normalized, at a constant velocity of 32.5 m/s with different angles were studied. In all cases of feed rates, impingement angles, particle sizes, and velocities of fly ash particles, it has been found that the erosion rate of the annealed tube is less than that of the normalized tube. Empirical correlations for erosion rate relating the velocity, size, feed rate, and impingement angle of the particles and elongation property of the target materials were arrived. Morphologies of the eroded surface were examined by scanning electron microscope (SEM).

Key words: erosion rate; economiser tubes; annealing; normalizing

1. Introduction

In large coal fired power stations, pulverized coal is burnt in the burners of boilers. To improve the overall thermal efficiency of the boiler plant, heat exchangers are used to extract residual heat energy from the flue gas and to transfer it to the feed water flowing through the tubes by the process of conduction and convection.

In coal fired power stations, about 20% of the ash produced in the boilers is deposited on the boiler walls and the superheater tubes. The rest of the ash is entrained in the stream of flue gas leaving the boiler. The ash particles collide with the surface of the economiser coil tubes and the material is eroded from the surfaces. In the advanced stage of erosion, the tubes become perforated. The tube elements fail once they cannot maintain their structural integrity. Such erosion shortens the service life of the tubes. Once this happens, the power plant has to be shut down and has to incur losses.

Erosion is a mechanical damage resulting in removal of the material from the surface by impact of particles. Earlier the mechanism behind this was believed due to the micro cutting mechanism [2]. Later it was proved that for ductile materials, the erosion mechanism involves the sequential plastic deformation process of platelet formation and crater formation due to forging and extrusion [3].

Through many studies and experiments done on the erosion of boiler tubes, it is estimated that 25%-30% of boiler tube failure occurs due to the ash erosion. Levy *et al*. [3] demonstrated that for the ductile material erosion rate is lower for the materials having higher ductility. Satyanathan [1] showed that 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*. [2] developed an analytical model to find the erosion rate based on the assumption that the erosion mechanism was due to micro cutting. Later it was demonstrated by Levy *et al*. [3] that micro cutting was not the primary mechanism by which ductile structural metal eroded. They conducted experiments and concluded that for the ductile material impacting particles cause severe localized plastic strain, which exceeds the

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strain of the material and cause the failure of deformed material, and for brittle materials the energy possessed by erodent particles causes cracking and removal as micro size pieces. Misra *et al*. [4] explained that the number of particles actually striking the surface does 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 *et al*. [10] tested the same material of specification with different micro structures like fine pearlite and coarse pearlite having different elongation percentages, and found that the erosion rate is less for the material having a higher elongation percentage.

Liebhard and Levy [11] had highlighted that erosion rates for the change in particle size are difficult to explain quantitatively because a number of factors like particle velocity and kinetic energy, the number of particles striking the target, interference between the striking and rebounding particles, the shape of particles, and the impact angle of particles are involved. Lyczkowski *et al*. [5] had stated that the clear understanding of erosion mechanisms is essential because erosion is very serious in the areas of combustion where coal is to be burnt cleanly. Mbabazi *et al*. [12] had conducted erosion tests on mild steel plates with three different fly ash samples from Lethabo, Matimba, and Matla power plants at different fly ash velocities and found that the experimentally calibrated general model yielded results that differed by less than 15% from the measured values. Oka *et al*. [6] stated that material removal is caused by the indentation process. It was found that the degree of load relaxation depends upon the ability of plastic flow for soft materials. They proposed a predictive equation containing material hardness and load relaxation ratio that could be related to find experimental erosion rate for different types of materials under a variety of impact conditions. Oka *et al*. [7] had expressed that mechanical properties of the material can be regarded as the main parameter for estimating erosion damage. Desale *et al*. [8] had expressed that the surface morphology of the specimen showed deep craters and a higher value of average surface roughness for angular particles. Harsha *et al.* [13] has conducted experiments for ferrous and non ferrous materials to find erosion rate against the cumulative weight of impinging particles. It was observed that erosion rate initially increases with the cumulative weight of impinging particles increasing and then reaches a steady state value. Wang and Yang [9] have demonstrated that for ductile materials the erosion is caused by the micro cutting and micro ploughing of 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 the material removal from the specimen surface.

In this paper, the samples of carbon steel tube materials of SA 210 GrA1 specification, currently in use for economiser coils in almost all power boilers [14], were tested in annealed and normalized conditions at BHEL's laboratory (recognized by National Accreditation Board for testing and calibration Laboratories) and found that in both conditions the mechanical test results met the requirements of ASME. The mechanical test results of annealed and normalized tubes of SA 210 GrA1 materials are given in Table 1.

Table 1. Properties of low carbon steel (target material)

Target Material	Heat treatment condition	Chemical composition / wt%			Tensile strength / MPa	Yield strength / MPa	Elongation / %
		C	Mn	Si			
SA 210 GrA1 (N)	Normalized	0.19	0.41	0.21	475	330	31
SA 210 GrA1 (A)	Annealed	0.19	0.41	0.21	425	260	39

2. Experimental setup

The experimental set up used for the present study is an air jet erosion test rig. The schematic diagram of the air jet erosion test rig is shown in Fig. 1. It is owned by the research and development lab of BHEL, Tiruchirappalli, India. The test rig was manufactured as per ASTM G76 standard. It consists of furnace, furnace controller and indicator, erodent feeding system and compressor. The furnace and furnace controller are used to heat and control the temperatures of both fly ash air stream and test specimen. The erodent feeding system is used to fluidize fly ash particles and make the fly ash air stream to impinge the test specimen. The erodent feeding system enables fly ash particles to deliver uniformly. The tester is capable of performing experiments by varying velocity, temperature, angle, and mass flow rate of fly ash particles.

3. Scanning electron microscope examination

The samples were cut from the eroded area of the annealed and normalized tube. The cross-sections of these samples were mounted, polished to diamond finish and etched in a 2vol% nital solution. The etched samples were examined under the scanning electron microscope and the images are shown in Figs. 2-3. SEM images of the eroded area show excessive piling up of deformed material that was extruded up from the craters produced by particle erosion and confirmed that the erosion mechanism was not simply by the micro cutting mechanism alone. Comparatively the number of platelets formed in the annealed specimen is more than that formed in the normalized specimen.

4. Experimental procedure

The test sample was weighed initially and then it was fitted at the Jet erosion test rig with a desired angle. The fly ash was taken in the chamber provided. The velocity and the concentration of fly ash particles were adjusted by controlling the air flow passing through the venturi. A jet of air with the fly ash particles passed through a nozzle and hit the surface of the sample with an angle chosen to place the sample. After doing the experiment for the scheduled time the sample was removed, it was cleaned and weighed to get the weight loss taken place. The amount of the ash used was also measured. The erosion rate was computed as the ratio of weight loss in the sample to that of the ash used. Effects of impingement of fly ash particles with other angles can be studied by varying the angle of placing the sample.

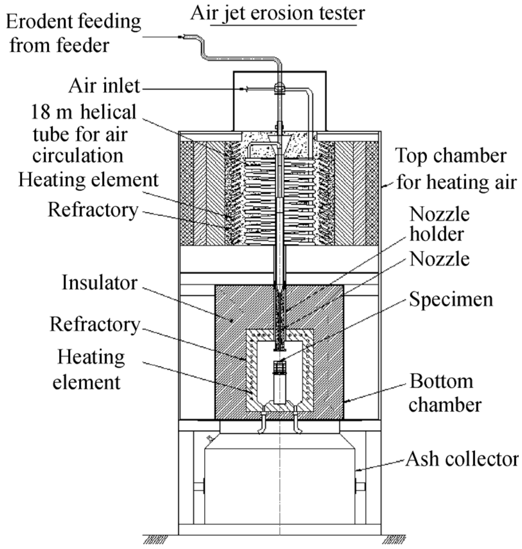

Fig. 1. Experimental set up.

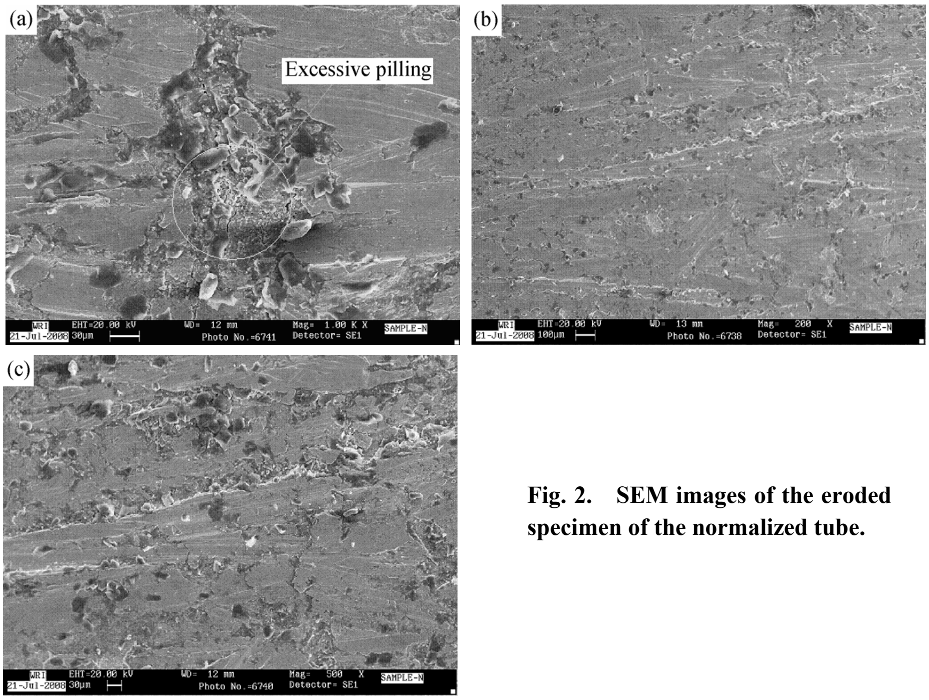

Fig. 2. SEM images of the eroded specimen of the normalized tube.

5. Results and discussion

5.1. Effect of velocity, impingement angle, feed rate, and particle size of fly ash particles on tube erosion

Fig. 4 shows the erosion rate of low carbon steel tubes at different impingement velocities ranging from 32.5 m/s to 40 m/s with the impingement angle of 30°. The data for graphs are obtained after the steady state of the erosion rate is reached. Erosion rate for SA 210 GrA1 (N) is higher than that for SA 210 GrA1 (A) at a given velocity attributing to ductility and elongation of the materials. In ductile materials, when fly ash particles impinge at 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, 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, which can be confirmed by noticing the platelets formed in the SEM micrographs shown in Figs. 2 and 3. It is the kinetic energy of the fly ash particle that has the greatest effect on the erosivity. The kinetic energy of fly ash particles, which is proportional to velocity, causes an increase in erosion rate when the velocity of fly ash particles is increased. When the ductility of the carbon steel economiser tube is more, the plastic deformation is increased and hence the erosion rate is decreased. So the annealed tube is having less erosion rate.

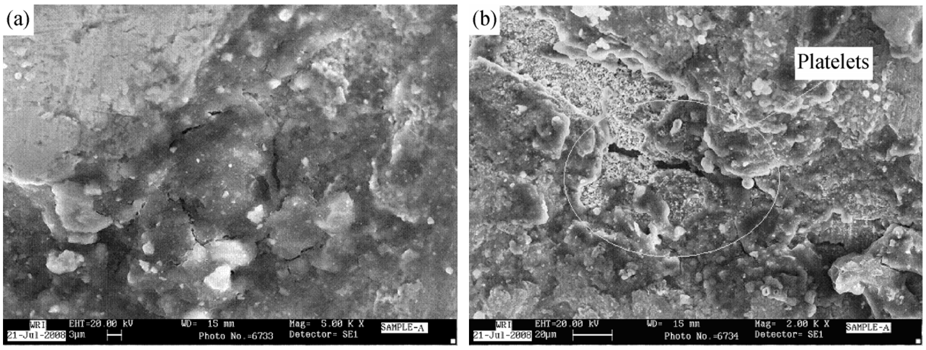

Fig. 3. SEM images of the eroded specimen of the annealed tube.

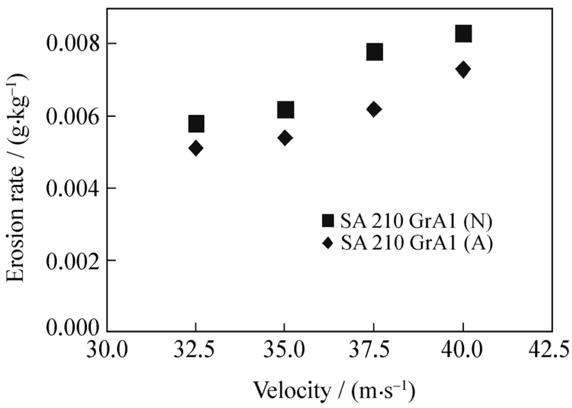

Fig. 4. Effect of the velocity of fly ash particles on tube erosion.

Fig. 5 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. The erosion rate increases with an increase in the impingement angle until 30° and thereafter erosion rate falls off rapidly. Hence at an angle of 30°, the erosion rate is found to be the maximum. This could be due to the increase in the penetration depth of the fly ash particle into the target material when the impact angle is increased. When the penetration depth of the particle is increased, plastic deformation in the target material is increased and thus erosion rate is reduced. For the same fly ash particles and impingement angle, erosion rate is mainly a function of target material properties. Also it is clear from Fig. 5 that the erosion rate of SA 210 GrA1 (A) is nearly 20% less than that of SA 210 GrA1 (N). The experiments were also conducted at 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 the impingement angle of 30°. The results are shown in Fig. 6. There is no increase in erosion rate for the increase in the feed rate of fly ash particles. At a 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 the target surface.

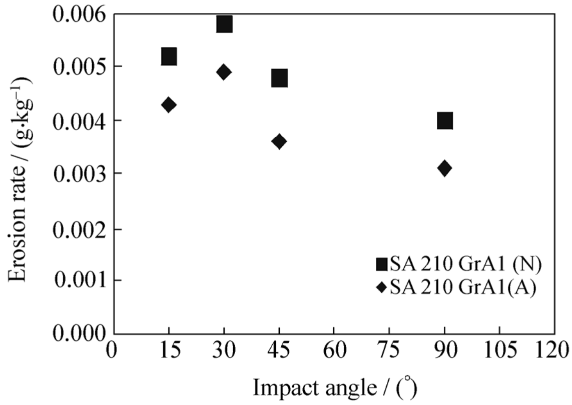

Fig. 5. Effect of impingement angle on tube erosion.

Fig. 7 shows that erosion rate increases with the increase in particle size from 50 to 125 μm and beyond this size there is no significant increase in it. More or less constant erosion rate with particle diameter above 125 μm is possible due to the combination of the 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 is low to be as effective in removing material as the 125 μm size particles or more. When the sizes of the particles are increased the number of the particles actually striking the surface does not proportionally increase due to the shielding effect provided by the rebounding particles. From the availability of the experimental data, correlations between erosion rate and the factors that influencing the erosion rate are arrived. The least square method is employed to develop the following empirical correlations.

$$E=0.66D_p^{0.545}V_p^{1.842}Q_p^{-0.312}(\sin\alpha)^{0.162}\varepsilon^{-0.586} \quad (\alpha<30°) \tag{1}$$

$$E=0.66D_p^{0.545}V_p^{1.842}Q_p^{-0.312}(\sin\alpha)^{-0.526}\varepsilon^{-0.586} \quad (\alpha>30°) \tag{2}$$

where D_p is the particle diameter, μm; E the erosion rate, g; Q_p the feed rate, g/min; V_p the velocity of the particle, m/s; α the impingement angle of particles, (°); and ε the elongation.

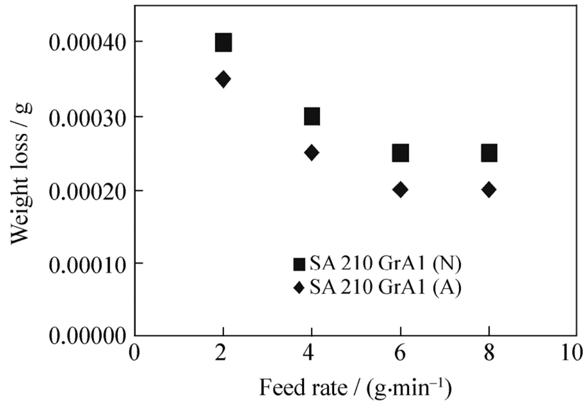

Fig. 6. Effect of the feed rate of fly ash particles on tube erosion.

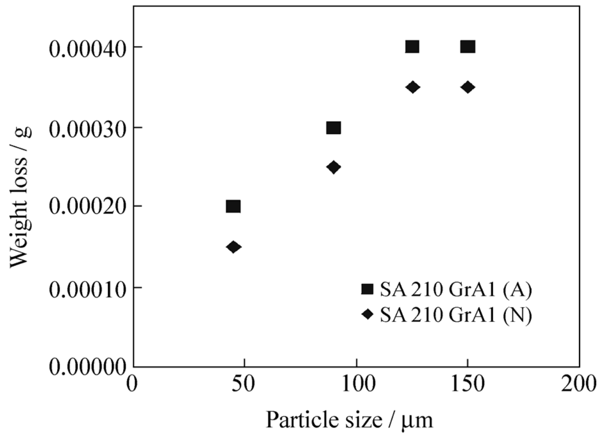

Fig. 7. Effect of the size of fly ash particles on tube erosion.

5.2. Effect of the heat treatment of the material on tube erosion

Table 2 gives a comparison of the erosion rate of a carbon steel tube in different heat treatment conditions (annealed and normalized) at a constant velocity of 32.5 m/s with different angles. The erosion is greater in case of the normalized material sample. As the normalized material has been cooled in air, it affects the transformation of austenite and affects the microstructure in many ways. There will be less proeutectoid ferrite in normalized hypo eutectoid steels compared with annealed ones. The faster cooling rate in normalizing will also affect the temperature of austenite transformation and the fineness of pearlite. In general, the faster the cooling rate, the lower the austenite transformation temperature and the finer the pearlite. In a normalized tube there is a fine lamellar pearlite whereas in an annealed tube there is a coarse lamellar pearlite. Due to this, normalized steel has more strength than the annealed one. Microstructures of annealed and normalized tubes of SA 210 GrA1 are shown in Fig. 8 which confirms the same.

Table 2. Erosion rate of the carbon steel tube in different heat treatment conditions at the velocity of 32.5 m/s

Impact angle / (°)	Erosion rate / (g·kg^{-1})	
	SA210 GrA1 (N)	SA210 GrA1 (A)
15	0.0052	0.0043
30	0.0058	0.0049
45	0.0048	0.0036
90	0.0040	0.0031

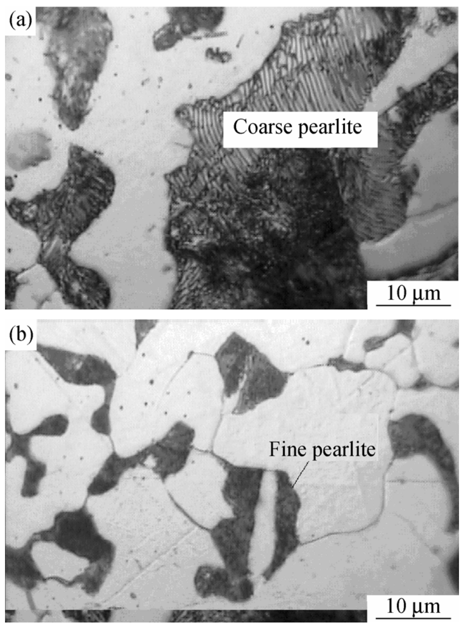

Fig. 8. Microstructures of the annealed tube (a) and the normalized tube (b).

6. Conclusion

The experimental investigations confirm that erosion rate of the normalized carbon steel tube is more than that of the annealed carbon steel tube. The study also confirms that when the velocity of fly ash particles is increased, the erosion rate also increases. When the impingement angle of fly ash particles on the target is increased from 15° to 90°, erosion rate is the maximum at 30° and then decreases. 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 it. In all the conditions considered in the experiment, erosion rate of the annealed carbon steel tube, having a higher elongation and ductility, is less than that of the normalized carbon steel tube. It is noticed that the erosion rates obtained through empirical correlations are found to fit with the experimental data within 15%. As it is permitted in ASME, by using the annealed carbon steel tube instead of the normalized carbon steel tube, the erosion rate of economiser coil tubes of power boilers can be reduced.

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References

[1] V.T. Sathyanathan, BHEL'S experience on pressure parts erosion and corrosion in fossil fuel fired boilers—An overview, [in] *Proceeding of Erosion and Corrosion Prevention in Boilers* (ECP), NIT, Tiruchirappalli, 2001, p.7.

[2] I. Finnie, J. Wolak, and Y. Kabil, Erosion of metals by solid particles, *Wear*, 2(1967), No. 3, p.682.

[3] A.V. Levy, The solid particle erosion behavior of steel as a function of microstructure, *Wear,* 68(1981), p.269.

[4] A. Misra and E.I. Finnie, On the size effect in abrasive and erosion wear, *Wear,* 65(1981), No.3, p.359.

[5] R.W. Lyczkowski and J.X. Bouillard, State-of-the-art review of erosion modeling in fluid/solids systems, *Prog. Energy Combust. Sci.*, 28(2002), p.543.

[6] Y.I. Oka, K. Okamura, and T. Yoshida, Practical estimation of erosion damage caused by solid particle impact: Part 1: Effects of impact parameters on a predictive equation, *Wear*, 259(2005), p.95.

[7] Y.I. Oka and T. Yoshida, Practical estimation of erosion damage caused by solid particle impact: Part 2: Mechanical properties of materials directly associated with erosion damage, *Wear*, 259(2005), p.102.

[8] G.R. Desale, B.K. Gandhi, and S.C. Jain, Effect of erodent properties on erosion wear of ductile type materials, *Wear*, 261(2006), p.914.

[9] Y.F. Wang and Z.G. Yang, Finite element model of erosive wear on ductile and brittle materials, *Wear,* 265(2008), p.871.

[10] A.V. Levy, The erosion of metal alloy and their scales, corrosion erosion wear of materials in emerging fossil energy systems, [in] *Proceedings of National Association of County Engineers* (NACE), Berkeley, 1982, p.298.

[11] M. Liebhard and A.J. Levy, The effect of erodent particle characteristics on the erosion metals, *Wear,* 15(1991), p.381.

[12] J.G. Mbabazi, T.J. Sheer, and R. Shandu, A model to predict erosion on mild steel surfaces impacted by boiler fly ash particles, *Wear*, 257(2004), p.612.

[13] A.P. Harsha and D.K. Bhaskar, Solid particle erosion behavior of ferrous and non-ferrous materials and correlation of erosion data with erosion models, *Mater. Des.*, 29(2008), p.1745.

[14] V. Kain, K. Chandra, and B.P. Sharma, Failure of carbon steel tubes in a fluidized bed combustor, *Eng. Failure Anal.*, 15(2007), p.182.