PREFACE

Erosion is a wear process that occurs when discrete solid particles strike a surface causing the removal of materials due to mechanical interaction between particles and the surface. High-temperature erosion wear is a serious problem in the coal-burning electricity generation industry which often suffers the direct and indirect loss due to the maintenance of the unit. Although, erosion takes place when impacting particles are stronger than the target material. Still, the contribution of target material properties is significant in the surface degradation mechanism. Amidst the most influencing parameters, the erosion rate of material under high-temperature conditions is not much excavated and thus needs more attention. In the present work, we aim to investigate the behaviour and performance against the erosion of Type 446 stainless steel under high operating temperatures and variable impact angles. This response of materials towards high-temperature erosion and the application of Type 446 stainless steel when used in the tubes working with temperature in the range of 200°C to 800°C restrict the investigators to observe the behaviour in the specified temperature zone.

In this study, erosion tests were conducted to evaluate the behaviour of Type 446 stainless steel at a higher temperature. The present investigation addresses this aspect by using Response Surface Methodology (RSM). RSM is a multivariate technique based on the fit of a polynomial equation to statistical data, with an objective to simultaneously optimize the levels of these variables to attain the best system performance. To approximate a response function to experimental data, a quadratic response surface, i.e., Central Composite Rotatable Design (CCRD) is used in the present study. Advances in computing power have enabled the application of Artificial Neural Network (ANN) in providing non-linear modelling for response surfaces and optimization. ANN offers an alternative to the polynomial regression method as a modelling tool. The present study deals with the influence of hot-corrosion enhanced solid particle erosion behaviour of Type 446 stainless steel used in heat exchangers. The test specimens were hot-corroded using NaCl and Na_2SO_4 deposits by the spray deposition technique. The coating of two salt mixture (75 wt% Na_2SO_4 + 25 wt% NaCl) easily degrades the Cr_2O_3 protective layer, thereby, penetrating the salts through the protective layer. The problems arising due to the synergistic effect of corrosion enhanced erosion are severe and their complexity is not thoroughly understood. Therefore, the pre-hot-corroded samples were exposed to erosion, to mimic the corrosion enhanced erosion behaviour. Both corrosion kinetics evolution and morphological development are investigated by means of weight gain measurements, metallographic examination, and identification of the corrosion products. Here, Ultra-sonic Shot Peening (USSP) treatment is an added factor to see its effect on hot corrosion resistance of this steel. This investigation highlights the dissemination of chromium to the surface forming a layer of chromium oxide, which is responsible to inhibit the outward diffusion of iron and reduce the iron-based scales formation.

As discussed above, chromium being a beneficial element, the selected material Type 446 stainless steel may offer to substitute the existing material in heat exchanger applications. Heat exchanger forms a vital part of many processes and has always been of great industrial importance. The requirement of heat exchangers such as improved efficiency, environmental needs, and cost-effectiveness demands reliable materials. Based upon principal selection criteria, the variety of materials chosen are ferritic steel 2.25Cr-1Mo, 9Cr-1Mo and austenitic stainless steel 304, 316 and, 321. Among these, ferritic steel is the preferred choice since it exhibits increased protection to stress corrosion cracking after annealing.

1.1 OUTLINE OF THE THESIS

The thesis has been organized into eight chapters and three appendices mentioned below:

Chapter 1 presents a literature review, introducing the description of "solid particle erosion" associated with power generation units especially heat exchangers. Relevant literature covering the fundamental aspects of erosion mechanism, models and parameters influencing erosion are discussed. Ferritic grade 446 stainless steel to meet the requirements of heat exchangers in the future is discussed. It covers the classification of ferritic grades, effects of alloying elements on the phase diagram to affect the mechanical properties of the material. Hot-Corrosion, its types, and the mechanism responsible for surface degradation during hot-corrosion of steels under salt environment are discussed. The hot-corrosion enhanced erosion behaviour of the steel which is a possible mechanism of material loss in the power generation units are also highlighted. The necessity to mitigate the corrosion-erosion degradation of materials has been discussed with all plausible techniques available. Also, emphasize is made on ultra-sonic shot peening technique (USSP) discussing the principle of its operation with the help of a schematic which is later used in this study. This chapter also details an introduction to the scope of the work including the motivation and objectives of the study.

Chapter 2 deals with the details of materials and experimental methodologies of hot-corrosion and high-temperature erosion. The initial part describes the characterization of microstructure, phases and mechanical properties. In the later section, hot corrosion set –up, salt spraying and deposition, and characterization of morphology using scanning electron microscope (SEM) and x-ray diffraction (XRD) is described. USSP set-up and characterization of nanostructure in the surface region of Type 446 stainless steel, carried out using Transmission Electron Microscope (TEM) is also detailed. Air-jet erosion tester as per ASTM G-76-95 is used for solid particle erosion testing.

Chapter 3 deals with preliminary experimentations carried out before the prime investigations. It comprises the identification of a suitable composition/grade of a ferritic grade for heat exchanger tubes. Type 446 stainless steel was selected after reviewing its chemical composition. Optical microscopy and SEM were used to investigate the presence of carbides. These carbides deteriorate the desired mechanical properties which directly influenced the erosion resistance. The tensile properties at elevated temperature and microhardness of the material are also tested. Sand used for erosion testing is characterized using SEM and particle size distribution.

Chapter 4 in this chapter the erosion behaviour of Type 446 stainless steel is reported. The effect of operating parameters on erosion is studied by varying the temperature and impingement angle under constant velocity. The feature of eroded zones and substrate deformation are examined. The roughness and depth of the scars formed are characterized. It is found that elevated temperature erosion is the dominant mechanism up to 750°C.

Chapter 5 deals with the modelling and optimization of parameters, like temperature, impact velocity and impingement angle, that effect high-temperature erosion of Type 446 stainless steel. A second-order polynomial model is developed using response surface methodology (RSM) following the central composite rotatable design (CCRD) method, and the effect of the main and interactive parameters on erosion rate is optimized. The roughness of the eroded surface is measured using Atomic force microscopy (AFM) to bring out the clear difference in erosion scars. A well trained artificial neural network

(ANN) with a back propagation algorithm is used to verify the optimized parameters for erosion rate generated by RSM.

Chapter 6 presents the pre-hot corrosion effect on erosion behaviour of Type 446 stainless steel in the simulated heat exchanger environment at elevated temperature. Samples were spray deposited using two salt mixture (Na_2SO_4/NaCl). Subsequently, low-temperature hot corrosion tests were carried out at 550, 650 and 750°C for 20 h. The morphology of oxide scales formed and depth of penetration was characterized using SEM. The elemental distribution through the diffusion process was characterized using energy-dispersive x-ray spectroscopy (EDS) mapping. The passive layer formed during corrosion underwent detachment of metallic flakes through cracking during the impact of erodent and was responsible for a significant change in erosion rate. Cutting, ploughing, lip formation, and particle embedment were identified as the operative mechanisms during erosion.

Chapter 7 is segmented into three parts: the first part deals with the process of improving materials resistance to corrosion with the help of surface modification. Ultrasonic shot peening is adapted as the technique to develop compressive stress on the surface. In the second part, the effect of surface nano crystallization (SNC), developed using USSP, on pre-hot corrosion-erosion behaviour of Type 446 stainless steel at elevated temperatures is studied. The transverse section of the USSPed specimens was characterized using an optical microscope (OM). Phase change was characterized using X-ray diffraction (XRD). The USSPed samples were subjected to isothermal low temperature hot corrosion (LTHC) tests for 20 h at 550, 650 and 750°C. The passive layer formed during LTHC was an outcome of sulfidation preceded by chlorination. The last part deals with erosion testing where Alumina (Al_2O_3) sand operated air-jet erosion tester was used to test the pre-hot corroded samples.

Chapter 8 presents the overall summary of the present investigation, including important conclusions and suggestions for further work.

Appendix (A-C) presents the Python programming, erosion rate values and list of publications.