ABSTRACT

A comprehensive understanding of the physical and chemical interactions between mating surfaces in relative motion is essential for the development of materials with high wear resistance. While strength, toughness, and ductility are crucial material properties, their optimization is a bit challenging due to their inverse relationship. Two-phase materials offer a promising solution to achieve a balance between these conflicting properties. The key principle is to leverage the advantageous effects of the second phase while minimizing the less desirable characteristics through the presence of the other constituent phases. The mechanical properties of two-phase systems are critically influenced by the size, distribution, shape, and volume fraction of the second phase. It is widely recognized that the wear behavior of materials is influenced by their mechanical properties, which, in turn, depend on the microstructure of the materials. Therefore, a detailed investigation of the morphology and volume fraction of the second phase in the microstructure and their impact on wear behavior is of utmost importance in the context of developing two-phase wear-resistant materials.

Wear encountered in the industry has been classified as the following types and their estimated relative occurrences are: Abrasive 50%; Adhesive 15%; Erosive 8%; Fretting 8% and Chemical 5%. The first study on the economic impact of tribology estimated that economic losses in England (1966) were 515 million British pounds, which corresponds to 1.5% of the gross domestic product (GDP). Subsequently, a similar exercise conducted in the USA reported an increase in wear losses to 180 billion dollars in 1984 (6% of the GDP). As a consequence, it is vital to become aware of different aspects of wear and take preventive steps to avoid the huge economic losses and catastrophic incidents due to wear. It is believed that a proper attention given to tribology, especially in education, research and application, could lead to economic savings between 1.3% to 1.6% of the GNP of any nation.

Metals and alloys are widely used in engineering for their wear resistance, overshadowing the

growing interest in ceramics and polymeric composites as tribomaterials. Consequently, a significant portion of wear research focuses on metallic materials. Despite the development of light weight wear resistant composites or alloys containing different reinforcements, steels continue to dominate a wide range of wear-resistant uses. Steels offer a distinct advantage by allowing the tailoring of their properties through simple heat treatment techniques, making them highly versatile. Among the various metallic materials, dual phase (DP) steel containing hard martensite islands embedded in relatively softer ferrite is one such two-phase material which holds a great promise in the pursuit of new wear resistant materials. DP steel possesses unique mechanical properties, including continuous yielding, high tensile strength, a high rate of work hardening, notable uniform and total elongation, good formability, high toughness to absorb shock load and excellent wear resistance make it particularly suited for different applications in the automotive sector (car bodies, chassis, bumpers, wheel discs, and rims), farm implements and pipelines, etc. and may also be a potential candidate for erosive wear applications.

Erosion is defined as a progressive loss of material from a solid surface because of the mechanical interaction between the solid surface and impinging solid or liquid particle. Erosive wear is a serious problem in the applications in the automotive sector (engine cradle, roof outer, door outer and floor panel), wire meshes, gas farm implements, pneumatic and hydraulic conveying of particulate materials (slurry), mineral processing and pipelines which often suffers the direct and indirect losses due to the shutdown of the machinery/industrial unit. Among the various factors affecting the erosive wear, impingement angle and impact velocity have been recognized as the two important parameters that significantly affect the erosion behavior of materials apart from the microstructure and mechanical properties.

In the light of above, it becomes imperative to explore the erosion characteristics of this important two-phase material i.e., DP steel. Therefore, the present investigation intends to analyze the erosive wear behavior of DP steels containing different martensite volume fraction under air jet erosion at different impingement angles and impact velocities, with a specific focus on the role of the microstructure and mechanical properties in affecting erosion behavior. The study also aims to investigate the effect of the microstructures i.e., ferrite–pearlite & ferrite-martensite on the corrosion behavior of DP steels by conducting experiments in a 3.5% NaCl solution. Hence, in the present study, the plain carbon steel containing 0.42 wt. pct. carbon have been intercritically annealed in the ($\alpha+\gamma$) region of Fe-C phase diagram at a constant temperature of 740°C for different holding times followed by water quenching to develop dual phase structures having four different martensite content. Normalized steel having the same carbon content has been used as a reference material for the purpose of the comparison. Additionally, fully martensitic steel (FMS) has also been developed by quenching the medium carbon steel from a single phase austenitic region so as to gain wider insight into the erosion and corrosion behavior of steel having fully martensitic structure. The erosive wear of medium carbon (N), DP and fully martensitic steels (FMS) has been studies at different impact velocities (30 m/s, 60 m/s, 90 m/s and 120 m/s) and impingement angles (15°, 45°, 75°, and 90°) with Al_2O_3 as an erodent. The corrosive performance of N and DP steels containing 39, 50, 65, and 79 vol.% martensite has been evaluated in a 3.5% NaCl solution using potentiodynamic polarization, EIS, and the gravimetric methods.

The present thesis has been organized into six chapters mentioned below:

Chapter 1 contains the introductory remarks highlighting the technological importance of the problem under investigation.

Chapter 2 begins with a critical review of the existing literature on the techniques of production and mechanical properties of DP steels. It is followed by an exhaustive survey on the various aspects of the erosive wear behavior of metallic materials in general and of steels in particular. The different types of wear and the erosive wear mechanisms in ductile and brittle materials have been outlined. The existing models for different types of erosive wear mechanisms are presented in the literature. The effects of the target material and temperature on the erosive wear behavior of the steels have been reviewed. The erodent parameters such as erodent shape, size, material, mass flow rate, impact velocity, and angle, which directly affect erosive wear behavior, have also been discussed. The limited knowledge of the role of microstructure and the erosive wear characteristics of DP steels has been given special attention as the role of these two variables has been particularly investigated in the present study. In the end, the motivation of the study and research objective is presented.

Chapter 3 outlines the experimental procedures followed in the present investigation. The method used to determine the chemical composition of steel is given. The details of the vertical tube furnace used for intercritical annealing heat treatment for the development of both the dual phase and the fully martensitic structure have been described, along with the parameters used for the heat treatment schedule. The procedures followed for the examination of microstructure and phases present i.e. optical microscopy, scanning electron microscopy, transmission electron microscopy, atomic force microscopy, and XRD have been illustrated. The descriptions of tests conducted for the evaluation of mechanical properties, such as hardness and uniaxial tensile strength, have also been described in this chapter. The fracture surfaces of the specimens have been examined under a scanning electron microscope. The procedure for sample preparation and details of the air jet erosion test rig has been presented. A detailed procedure of characterization of erodent particles, erosion testing along impact velocity calibration and test parameters is provided. Sample weight losses have been measured at different intervals of time to evaluate the loss of material caused by impinging particles at different angles and velocities. The surface and sub-surface of eroded specimens have been examined under Scanning Electron Microscope (SEM). The procedures for carrying out corrosion test have been described along with the detailed of the setup used. Finally, the corroded surface of steels has been analyzed using scanning electron, energy dispersive, and atomic force microscopy.

Chapter 4 begins with the results on chemical composition, microstructure, and mechanical properties characterizing medium carbon normalized (N) steel, dual phase (DP) steels, and fully martensitic steel (FMS). This is followed by the presentation of the results of the tests conducted to examine the erosive wear of N and DP steels at four impact angles viz., 15º, 45º, 75º, and 90º and at a fixed impact velocity of 90 m/s and the surface & sub-surface examination of eroded specimens. The observed erosive behavior has been discussed in the light of the features seen on the eroded surface and sub-surface as well as the microstructure and mechanical properties of steels. The martensite content in DP steels has been evaluated using ImageJ software using optical micrographs. The increasing time of holding during intercritical annealing followed by water quenching results in an increasing volume fraction of martensite in medium carbon DP steels and a further increase in holding time leads to the formation of fully martensitic steel. The DP steels developed after holding times of 2, 3, 3.5 and 4.0 minutes are designated as DP2, DP2, DP3, DP3.5, and DP4 steels and their respective martensite volume fractions (MVF) are 0.39, 0.50, 0.65 and 0.79. The XRD pattern shows the martensite and ferrite peaks in the DP steels. The Vickers hardness measurements point towards an increasing hardness with martensite volume fraction and the variation of microhardness with intercritical annealing time shows the indirect relation of ferrite and martensite hardness with intercritical annealing time. The DP steels show a continuous yielding behavior under tension, confirmed by the absence of a yield point in the stress-strain curve, while a clear yield point phenomenon is visible in the stress-strain curve of normalized steel. The UTS has the highest value for fully martensitic steel and the lowest for normalized and DP steels falling in between. The UTS in DP steels increases with martensite content. The percentage elongation decreases with increasing volume fraction of martensite in the DP steels. The normalized steel shows a typically ductile mode of fracture, whereas the fully martensitic steel shows a typically brittle fracture. The DP steel with a 65% martensite volume fraction shows the mixed mode (ductile + brittle) of fracture with increasing dominance of brittle mode with the martensite content. However, a brittle mode of fracture has been observed in DP steel with a martensite volume fraction of 0.79.

The results of erosion tests indicate that steady state erosion rate decreases with increasing angle of impact for N steel as well as DP steels. It has been explained on the basis of vertical and horizontal components of kinetic energy of the impinging particles and the area of contact between impacting particles and the eroded surface. However, DP steels show a significantly reduced erosion rate in comparison to N steel reflecting the role of microstructure and hardness. Steady state erosion rate also decreases with increasing martensite content in DP steels from 39 to 79% and DP4 steel containing 79% martensite shows the best performance in terms of erosion resistance. The mechanism of material removal has been observed to change from micro-ploughing to crater formation with the increase in the angle of impingement. Micro-ploughing, lip formation, and embedded chips have been identified as the operative erosion mechanisms for N steel, whereas ploughing, craters and cracks formation have been shown to be the operative erosion mechanisms for DP steels. A mechanism of erosion in N and DP steels has also been proposed and explained by considering different regions of interest, i.e., ferrite, martensite, and ferrite-martensite interface. The velocity component of impinging particles has been used to understand the mechanisms.

The results pertaining to corrosion behavior of normalized and DP steels as analyzed by Potentiodynamic polarization, energy impedance spectroscopy, and gravimetric method are also included in the chapter. The corrosion rate has been observed to increase with martensite content, except for DP3.5 with 65 vol.% martensite, which has shown the lowest corrosion rate among all the steels. The observed behavior has been explained on the basis of the self-corrosion rate of ferrite, pearlite, martensite, the number of galvanic couples between the constituent phases and the shape of the martensite. A mechanism of corrosion in N and DP steels has also been proposed and discussed.

Chapter 5 describes the results on the erosive wear characteristics of medium carbon (N), DP (DP), and fully martensitic (FMS) steels at different impact velocities (30 m/s, 60 m/s, 90 m/s, and 120 m/s) and impingement angles (15°, 45°, 75°, and 90°) with Al_2O_3 as the erodent particle. The results have been discussed in the light of the microstructure of different steels. he steady state erosion rate increases with an increase in impact velocity for all materials, whereas it decreases with an increase in impact angle for all steels except for FMS. At low and high impact angles, N steel exhibits the highest erosive wear characterized by micro cutting and ridge formation. FMS has shown the highest erosion rate compared to all the steels due to its inherent brittle nature except at 90° and 120 m/s, which makes it prone to easy crack propagation. In DP steel, the cracks get arrested by the hard martensite island and their easy propagation is inhibited, which leads to only low angle cutting and micro ploughing. This reflects the advantage of using a dual phase structure. DP steels showed higher erosion resistance because they offer a balanced combination of strength and ductility at an adequate level of toughness. The material removal in N steel is found to occur by micro cutting, ridge, and crater formation, whereas shallow micro ploughing and craters are observed in FMS. However, the material removal for DP steels has been found to occur due to a combination of micro ploughing, micro cutting and crater formation. A mechanism of material removed is proposed and described based on the behavior of constituent phases in the microstructure of steels studied in the current investigation.

Chapter 6 presents the major conclusions of the current study on microstructure, mechanical properties, and erosive wear behavior of normalized steels, medium carbon DP steels, and fully martensitic steel in the context of their constituent phases.