STUDIES ON EROSIVE WEAR CHARACTERISTICS OF DUAL PHASE STEEL

Thesis submitted in partial fulfillment for the
Award of Degree

Doctor of Philosophy

By

POOJA VERMA

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI - 221005

Roll No. 17131008 2023

CHAPTER 6:

CONCLUSION

CHAPTER 6

CONCLUSIONS

The present investigation on the evaluation of the erosive and corrosive behavior of normalized (N) steel and dual phase (DP) steels (DP2, DP3, DP3.5 and DP4) and fully martensitic (FMS) steels may be concluded in four different parts corresponding to (i) development of DP steels and their mechanical properties, (ii) erosive wear at a fixed speed and different angles of impact, (iii) corrosion behavior of DP steels, and (iv) Effect of microstructure and martensite content on erosive wear of DP steels at different impact velocities and impingement angles.

6.1 Mechanical Properties

1. The volume fraction of martensite in DP steels initially increases with increasing intercritical annealing time at 745°C. However, the amount of martensite saturates after intercritical holding for 5 minutes at 745°C in medium carbon steel containing 0.42% carbon.

2. The hardness, yield strength (YS) and ultimate tensile strength (UTS) in DP steels increase with increasing amount of martensite, which is a hard and load bearing phase. However, the ductility measured in terms of percentage elongation and percentage reduction in area decreases with increasing martensite volume fraction.

3. The microhardness of the martensite decreases whereas, that of the ferrite in DP steels increases with increasing time of intercritical annealing due to the increased diffusion of carbon from austenite (which on water quenching transforms to martensite) to ferrite.

4. The micro hardness of ferrite increases whereas the micro hardness of martensite decreases with increasing intercritical annealing time due to the redistribution carbon between the phases. Initially, the austenite that forms by the dissolution of cementite plates has the higher carbon content and the micro hardness of martensite developed from this austenite is higher. As the time increases, the carbon diffusion occurs from austenite to ferrite leading to a decrease in the carbon content of austenite, resulting in a martensite of lower hardness.

5. Normalized steel and DP2 steel containing 39% of martensite show a ductile mode of fracture, whereas DP3 (50 % martensite) and DP3.5 (65% martensite) steels exhibit the mixed mode (ductile and brittle) of fracture. However, DP4 steel (79% martensite) and FMS steel have shown a brittle mode of fracture.

6.2 Erosion Behaviour at a Fixed Velocity and Different Impact Angles

6. The erosion rate decreased with increasing angle of impingement from 15°-90° for both N and 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.

7. The DP steels had a higher resistance to erosion in comparison to normalized steel and the same has been attributed to the increased hardness of the DP steel due to change in microstructure from ferrite-pearlite to ferrite-martensite which inhibits the easy propagation of crack. The DP4 steel containing 79% martensite showed the best performance in terms of erosion rate at all the angles of impact.

8. The erosive wear in the N steel occurs by a combination of lip/chip formation and micro-ploughing at impingement angles of 15°, 45° and 75° whereas the same occurs by the formation of chips and craters at 90° as revealed by SEM examination of eroded surfaces.

9. In the DP steels, the erosive wear took place by micro-ploughing and chips formation at the impingement angles of 15° and 45° whereas formation of cracks and craters at 75° and 90° was main cause of material removal.

6.3 Corrosion Behaviour

10. N steel shows a higher corrosion rate as compared to DP2, DP3, and DP3.5 steel, due to the formation of micro-galvanic cells between ferrite and cementite within the pearlite region and also between pearlite and pro-eutectoid ferrite, as well as the self-corrosion of ferrite and pearlite.

11. The corrosion rate increases with the increasing intercritical annealing time (MVF), except for DP3.5; having 65% martensite has shown the minimum corrosion rate as compared to all other steels. It has been attributed to the relatively smaller number of galvanic cells and the decreased self-corrosion rate of the martensite phase.

12. The DP4 steel containing 79 % martensite has the highest corrosion rate among all the steels including N steel which has been ascribed to the higher self-corrosion rate of martensite which dominates over the decreased micro-galvanic corrosion due to a smaller number of the galvanic couple.

13. The corrosion behavior of DP steels in 3.5% NaCl solution is found to be influenced by the amount and the shape of the martensite from island to lath type.

6.4 Erosion Behaviour of DP Steels at Different Impact Angles and Velocities

14. DP steels show a higher resistance to erosion in comparison to N steel and FMS when eroded by Al_2O_3 particles, and it has been attributed to an adequate combination hardness and toughness in DP steel due to change in microstructure from ferrite-pearlite to ferrite-martensite. This reflects the advantage of a dual phase structure in comparison to either a ferritic-pearlitic or fully martensitic structure.

15. Steady state erosion rate decreases with the increase in martensite volume fraction and increases with impact velocity in DP steels. However, the steady state erosion rate has been found to decrease with impact angle for N and DP steels whereas it is observed to increase for FMS. DP steels have shown higher erosion resistance than N steel and FMS, reflecting the role of microstructure (ferrite + martensite) in affecting the erosion behavior of steels.

16. At *low angle-low velocity*, the material removal in N steel occurs by micro cutting and ridge formation, in DP steels it takes place by a combination of micro ploughing and micro cutting and in FMS by shallow micro ploughing.

17. At *high angle-high velocity*, the material removal in N steel occurs by ridge formation & low angle cutting, in DP steels by a combination of crater formation & low angle cutting and in FMS by the formation of deep craters.

18. The difference in the steady state erosion rates of N, DP and FMS steels decreases as one moves from *low angle-low velocity* condition to *high angle-high velocity* condition at which the erosion rates of N and DP steels become almost same, whereas the erosion rate of FMS is higher than both of N and DP steels. Hence, it is concluded that DP steel provides a better resistance to erosion and offers itself to be utilized as a potential material for applications involving erosion under the conditions used in the present study.

19. At *low angles and high velocities*, erodent particles possess substantial kinetic energy and a sufficient contact area with the target material which lead to a relatively higher erosion rate under these conditions depending on the microstructure of the steel.

20. At *low angles and high velocities,* in N steel having (ferrite + pearlite) the removal of material ensues by a mechanism wherein, as the erodent particles strike the pearlite structure the stacks of pearlitic plates deform and resist further deformation. Initially, the shallow micro cutting and the material accumulation occur during the early stages of pearlite plate deformation which eventually lead to their detachment due to successive particle impacts.

21. At *low angles and high velocities*, a deep micro ploughing occurs if the particle strikes on the ferrite phase in DP steel due to the presence of the hard martensite

phase, which prevents cutting but allows the material accumulation around the impacting particle. However, when the particle impacts the martensitic region, the adjoining ferrite phase does not permit the generation of micro-cracks by absorbing the majority of the impact energy due to its sufficient toughness.

22. The material removal in FMS steel at occurs by the micro ploughing due to the presence of hard martensite needles, which prevent deep penetration or material cutting during *low angle-high velocity* particle impacts.

23. At *high angles-high velocities* the material removal in N steel occurs through the formation of shallow craters when particles impact the fully pearlitic region. Additionally, ridge formation and low angle cutting occur in the ferritic region.

24. The *high angle-high velocity* impact of particles on DP steels causes significant plastic deformation leading to the removal of material by ridge formation and low angle cutting in the ferrite region. However, the material removal in the martensitic region occurs by shallow crater formation.

25. *At high angle-high velocity* the material removal in fully martensitic steel (FMS) occurs via the formation of craters on the surface, from which micro cracks nucleate, grow, propagate and get connected to each other. The coalescence of cracks results in deep and wide craters, and eventually the material spalls off the surface of steel.

26. The DP steels with an optimum amount of ferrite and martensite provide better resistance to erosion or corrosion than pearlitic or fully martensitic steels and offer themselves as potential candidates for components that work under erosive and/or environments.

FUTURE WORK

Erosion behaviour of DP steel containing different amounts of martensite has been investigated in the present study at different impact velocity and impingement angles under air jet erosion whereas the corrosion behaviour has been examined separately in 3.5% NaCl solution. However, there are a variety of applications such as automotive components, mineral processing, mining, power plants and pipeline transportation of slurry etc. where the component has to work simultaneously under erosive and corrosive environment. Some of the below-mentioned studies may be undertaken in future.

1. DP steels can be heat treated to attain tempered martensite and their mechanical properties as well as the erosion and corrosion behaviour can be examined.
2. The erosion studies could be conducted using different types of erodent material with different size of particles to explore the effect of erodent hardness as well as the particle size on the material removal.
3. The combined erosive-corrosive behavior of dual-phase steels can be assessed by varying the concentrations of erodent particles in the slurry.
4. Performing Finite Element Analyses (FEA) on erosion tests can provide a thorough understanding of deformation mechanisms and help optimize erosion parameters.