CHAPTER 5

CONCLUSIONS

The evaluation of friction and wear behavior of atmospheric plasma spray deposited Ni-Al-Ag-MoS_2 (NAMB0), Ni-Al-Ag-MoS_2-5 wt. % hBN (NAMB5) and Ni-Al-Ag-MoS_2-10 wt. % hBN (NAMB10) coatings has led to certain salient conclusions which are presented in three parts; (a) room temperature (RT) behavior of coatings under normal loads of 5, 10, 15 and 20 N and sliding speeds of 0.5 m/s, (b) tribological behavior at a constant load 5 N and speed 0.3 m/s but at different temperatures ranging from RT to 800 ° C and (c) elevated temperature (RT to 800 °C) wear under different speeds of 0.3, 0.5, 0.7 and 0.9 m/s and at a fixed load of 5 N.

5.1 COATING CHARACTERIZATION

1. The Ni based composite coatings Ni-Al-Ag-MoS_2, Ni-Al-Ag-MoS_2-5 wt. % hBN and Ni-Al-Ag-MoS_2-10 wt. % hBN could be successfully deposited on Inconel substrate by atmospheric plasma spray route. All the coatings exhibit a typical lamellar microstructure. XRD analysis of as deposited coatings indicated that powders are deposited without any oxidation or disintegration under the investigational spraying constraints and solid lubricants are available as such in the coatings.

2. All the coatings exhibit a typical lamellar microstructure, however, the coating containing 5 wt. % hBN i.e. NAMB5 exhibits a relatively compact and dense structure than others.

3. The porosity of coatings has been found to increase with addition of hBN in the present study. The coating containing no hBN i.e., NAMB0 has the least porosity 4.8 ± 0.7%, whereas NAMB5 and NAMB10 have 8.0 ± 1.0% and 24 ±1.4%, respectively and the increase in porosity has been ascribed to the poor integration of hBN in the matrix.

4. The hardness of the coatings has been found to decrease with increasing amount of hBN in coatings. The coating containing no hBN i.e., NAMB0 has the highest hardness of 182.4 $HV_{0.2}$ whereas the coatings with 5 wt. % and 10 wt. % hBN namely, NAMB5 and NAMB10 have 164.6 $HV_{0.2}$ and 155.3 $HV_{0.2}$, respectively. A decrease in hardness with addition of hBN has been attributed to the poor wettability and sinterability of hBN which hampers the close contact between other constituent materials of coating and hence, the process of densification.

5.2 FRICTION AND WEAR BEHAVIOR OF COATINGS

5.2.1 ROOM TEMPERATURE TRIBOLOGICAL BEHAVIOR UNDER DIFFERENT LOADS AND A FIXED SPEED

5. All the coatings have been found to show a fluctuating trend of variation of coefficient of friction with time at all the loads (5, 10, 15 and 20 N) but the amplitude of variation has been observed to be more at a load of 5 N in comparison to that at 15 N. It has been attributed to the better compaction of the wear debris due to relatively higher frictional heating which led to the formation of a smoother layer at the surface. The NAMB5 coating has shown the lowest COF at all the loads.

6. The average coefficient of friction and wear rate have been found to decrease with increasing load from 5 to 15 N beyond which an increase is observed for all the coatings till 20 N. However, NAMB5 and NAMB10 have shown a lower coefficient of friction as well as rate of wear in comparison to NAMB0. The observed behavior has been explained on the basis of (i) the formation and extent of compaction of the transfer layer containing solid lubricant on the sliding surface, (ii) the transfer of solid lubricant(s) from coating to counterface alumina ball and (iii) the generation and presence of new lubricating phases due to tribo-chemical reactions at the interface caused by the temperature rise. The NAMB5 coating has shown the lowest friction (0.29) at 15 N and 0.5 m/s among all the coatings.

7. A decrease in coefficient of fiction and wear rate is found to occur with addition of hBN in the coatings. The reduced friction and wear rate in coatings having hBN has been attributed to the synergistic action of hBN, in conjunction with MoS_2 and Ag in improving the tribological performance of these coatings. However, NAMB10 (containing 10 w. % hBN) has a relatively higher coefficient of friction and wear rate at all the loads in comparison to NAMB5 (containing 5 wt. % hBN) indicating that 5 wt. % hBN is good enough for enhancing the tribological performance of such coatings.

8. At room temperature, the mechanism of wear in NAMB0 coating is a mixture of ploughing and delamination. The mechanism of wear in NAMB5 coatings are adhesion and transfer layer formation under all the loads, whereas for NAMB10 coating is a mix of adhesion and delamination.

5.2.2 TRIBOLOGICAL BEHAVIOUR FROM RT-800 °C AT A FIXED SPEED AND CONSTANT LOAD

The tests conducted to explore the friction and wear characteristics of NAMB0, NAMB5 and NAMB10 coatings under different temperatures (RT, 200, 400, 600 and 800 °C) at a contact load of 5 N and a fixed sliding speed of 0.3 m/s have resulted in following conclusions:

9. All the coatings i.e., NAMB0, NAMB5, NAMB10 show a fluctuating trend of variation of friction with temperature with the amplitude of fluctuations being similar for all the coatings at RT and 400 °C. However, the amplitude of fluctuations is small at the highest temperature of 800 °C for all the coatings in comparison to that at RT and 400 °C. At 800 °C, the variation of friction coefficient is relatively smooth for NAMB5 coating in comparison to NAMB0 and NAMB10 and NAMB5 coating has the lowest coeffieinct of friction for the complete duration of sliding at all the temperatures.

10. The average COF of NAMB0 coating first decreases from RT to 200 °C and increases thereafter till 400 °C. A decrease in coefficient of friction from RT to 200 °C has been attributed to presence of Ag and MoS_2 whereas an increase at 400 °C has been ascribed to the loss of effectiveness of MoS_2. A continuous decrease in coefficient of friction beyond 400 °C has been credited to the formation of lubricous silver molybdates, NiO and nickel molybdates.

11. The average COF of coatings containing hBN i.e. NAMB5 and NAMB10 shows a continuously decreasing trend from RT to 800 °C. Also, the average coefficient of friction has been found to decrease with addition of hBN in coatings and it has been attributed to the synergetic action of hBN with Ag and MoS_2. The NAMB5 coating has shown the lowest COF (0.23) at 800°C at 5 N and 0.3 m/s.

12. The wear rate of NAMB0 coating first decreases in low temperature regime (RT to 200 °C) due to lubricating effect of MoS_2 thereafter it increases up to 400 °C. Beyond 400 °C, the wear rate decreases continuously due to formation of lubricous silver molybdates, NiO and nickel molybdates compounds which act as high temperature lubricants.

13. The wear rate of coatings containing hBN i.e. NAMB5 and NAMB10 has been observed to decrease continuously with increasing temperature from RT-800 °C. Among all the coatings, NAMB5 coating has shown a relatively lower rate of wear at all the temperatures and with lowest rate (2.3×10^{-5} mm^3/Nm) at 800°C. The decreasing rate of wear for NAMB5 and NAMB10 coatings has been attributed to (i) the formation of Ni and Mo oxides, silver molybdates, (ii) the transfer of hBN to the counterface and (iii) the synergetic action of hBN in conjunction with Ag, MoS_2 at all the temperatures.

14. The mechanism of wear in NAMB0 coating is a mixture of ploughing and abrasive wear at RT, and the combination of abrasive and adhesive wear at 200 °C whereas, at 400 °C the tribo-oxidation and abrasion are dominating.

At 600 and 800 °C the glaze layer (trio-layers) formation and adhesion are dominating wear mechanism for this coating. For NAMB5 coating the operative mechanisms are adhesion from RT to 400 °C and glaze layer (tribo-layers) formation at elevated temperatures. The mechanism of wear for NAMB10 coating is abrasive at RT whereas the dominating mechanisms of wear from 200 to 800 °C are tribo-oxidation and adhesion.

5.2.3 TRIBOLOGICAL BEHAVIOUR AT DIFFERENT TEMPERATURES (RT to 800 °C) UNDER DIFFERENT SPEEDS (0.3, 0.5, 0.7 and 0.9 m/s) AND AT A CONSTANT LOAD OF 5 N

15. The friction coefficient and wear rate for all the coatings have been found to decrease with increasing temperature with the exception of NAMB0 coating containing Ag and MoS2 only, which has shown an increase in friction coefficient from 200 to 400 °C at all the sliding speeds due to loss of lubricating action of MoS2.

16. At a particular temperature, the average COF is observed to decrease with increasing speed from 0.3 to 0.7 m/s followed by a slight increase till 0.9 m/s for all the coatings. All the coatings have shown the minimum COF at a speed of 0.7 m/s. However, NAMB5 has shown a relatively lower COF under all the speeds in comparison to NAMB0 and NAMB10 with a minimum COF of 0.1 at a sliding speed of 0.7 m/s. The observed behavior has been attributed to the formation of a transfer layer, its degree of compaction and extent of cover provided to the underlying substrate.

17. The average COF for NAMB0 coating is observed to decrease from RT to 200 °C followed by an increase thereafter till 400 °C before decreasing again beyond that till 800 ^{o}C and the trend of variation is same at all the speeds. However, for the coating containing hBN i.e., NAMB5 and NAMB10, COF decreases consistently with increasing temperature at a particular speed. The NAMB5 coating has shown the lowest COF from RT to 800 °C at all the temperatures with the lowest value of 0.1 at 0.7 m/s at 800 °C.

18. At a particular temperature, the wear rate for all the coatings is observed to decrease with increasing speed from 0.3 to 0.7 m/s followed by a marginal increase till 0.9 m/s. NAMB5 coating has shown a consistently lower wear rate at all the speeds for all the temperatures with a minimum value of $2 \times 10^{-5} mm^3/Nm$ at a sliding speed of 0.7 m/s. The observed behavior has been explained on the basis of the formation of transfer, its degree of compaction and the protection provided by this layer to the underlying material.

19. At a particular speed, the wear rate of NAMB0 composite coating decreases from RT-200 °C, followed by an increase till 400 °C and a decrease again as the temperature is raised beyond 400 °C and same trend of variation is observed at all the speeds. The wear rate of composite coatings NAMB5 and NAMB10 is observed to decrease consistently with increasing temperature from RT to 800 °C. However, NAMB5 coating has shown the lowest wear rate at all the temperatures and speeds in comparison to other coatings.

20. The mechanism of wear in NAMB0 coating is a mixture of ploughing, abrasion, adhesion, delamination and glaze formation depending upon the combination of speed and temperature. However, operative mechanisms for NAMB5 are a mix of adhesion and abrasion depending on the sliding speeds from 0.3 to 0.9 m/s, from RT-400 °C and glaze layer (tribo-layers) formation & adhesion at elevated temperatures at all the sliding speeds.

21. The mechanism of wear for NAMB10 coating is abrasive at RT, whereas from 200 °C to 400 °C the tribo-oxidation and adhesion are dominating mechanisms. However, a mix of adhesion and glaze layer (tribo-layers) formation are the operative mechanisms at 600 and 800 °C.

22. An improved tribological performance of coatings having hBN (as all the coatings have same amount of Ag and MoS_2) reflects the potential and effectiveness of hBN in working synergistically with Ag and MoS_2 in reducing friction and wear in a broad range of temperatures from RT to 800 °C.