CONCLUSIONS

The present investigation on the evaluation of tribological performance of copper based hybrid composites containing either a combination of hard and soft phases (Al_2O_3, MoS_2 and *h*-BN) or rGO-MoS_2 hybrid as reinforcement phase has led to several salient conclusions which are presented in two sections corresponding to two different approaches followed in this study: (i) friction and wear behavior of Al_2O_3, MoS_2 and *h*-BN reinforced composites and (ii) mechanical and tribological behavior of rGO-MoS_2 reinforced copper based composites.

7.1 FRICTION AND WEAR BEHAVIOR OF Cu-Fe-Al_2O_3, Cu-Fe-Al_2O_3-MoS_2 AND Cu-Fe-Al_2O_3-MoS_2-*h*-BN COMPOSITES

1. The hardness of Copper has been found to increase with addition of Fe and Al_2O_3 nano particles which has been attributed to the thermal expansion mismatch. The addition of MoS_2 in Cu-Fe-Al_2O_3 composite also increased the hardness of the composite due to uniform dispersion of MoS_2. However, a reduction in hardness with addition of *h*-BN in Cu-Fe-Al_2O_3-MoS_2 has been ascribed to the poor sintering characteristics of *h*-BN.

2. The coefficient of friction coefficient has been found to increase with load (from 2 to 4 N) for pure Cu due to abrasion and decreased thereafter till 8 N due to frictional heating and resulting plastic deformation. However, the coefficient of friction for Cu-Fe-Al_2O_3 (CA) composite has been found to increase with increasing load and the same has been attributed to the change in wear mechanism from delamination to third body abrasion.

3. The coefficient of friction for composite Cu-Fe-Al_2O_3-MoS_2 (CAM) increases from 2 to 4 N load with no measurable change further till 8N and it has been attributed to the formation of a compact layer containing MoS_2 which provides low shearing interface between mating bodies. However, an increase in coefficient of friction with increasing load from 2 to 6 N has been observed for Cu-Fe-Al_2O_3-MoS_2-*h*-BN (CAMB) followed by a decrease till 8 N due to the formation of a mechanically mixed layer.

4. The coefficient of friction at 8N is observed to be the least for pure copper because plastic deformation and adhesion, whereas in composite Cu-Fe-Al_2O_3 (CA) abrasion and oxidation are responsible for high frictional force. The moderate friction shown by Cu-Fe-Al_2O_3-MoS_2-*h*-BN (CAMB) has been attributed to the sum of abrasion and plastic deformation. However, a relatively higher coefficient of shown by CAMB has been attributed to the poor sintering characteristics of *h*-BN and its poor synergy with other constituents which resulted in *h*-BN pull out.

5. The wear rate has been found to decrease with increase in load from 2 to 4 N followed by a decrease thereafter till 8 N for all the composites except CA for which a continuous increase in wear rate is observed with load. The presence of a compacted transfer layer containing MoS_2 in CAM and CAMB is believed to be responsible for a decrease in wear rate with increasing load from 4 to 8 N whereas a continuous increase in wear date for composite CA has been attributed to oxidation and fatigue fracture.

6. The wear rate of composite CAM is observed to be minimum among all the composites which has been attributed to the compact layer formation over the worn surface, inhibiting the metal to metal contact, thus reducing the wear rate, whereas maximum wear rate is recorded for composite CA, attributed to the delamination and oxidation at low loads and three body abrasion at higher loads which has been confirmed by the SEM micrograph and XRD of worn track.

7. The prevailing wear mechanism shown by pure Copper is severe abrasion at low loads and mild adhesion at higher loads, while the same for composite CA is a combination of fatigue assisted delamination and oxidation at low loads and three body abrasion at relatively higher loads. However, delamination has been observed to be the prevailing wear mechanism for CAM composite at all the loads, whereas, composite CAMB has exhibited a transformation of wear mechanism from plastic deformation to mild adhesion with increasing load under the conditions of sliding used in the present study.

8. The room temperature tribological performance of hybrid composite CAMB, containing a combination of MoS_2 and *h*-BN has been found to be inferior to the composite CAM containing MoS_2 only reflecting the absence of any synergetic action between *h*-BN with MoS_2 under the regime of loads (4 to 10 N) used in the present investigation.

7.2 MECHANICAL AND TRIBOLOGICAL BEHAVIOR OF rGO-MoS_2 REINFORCED COPPER BASED COMPOSITES

7.2.1 SYNTHESIS OF rGO-MoS_2 REINFORCED COPPER BASED COMPOSITES SINTERED AT DIFFERENT SINTERING TEMPERATURES AND THEIR MECHANICAL PROPERTIES

9. The nanoparticles of rGO-MoS_2 hybrid have been synthesized successfully using a hydrothermal approach. The grafting of MoS_2 nano ribbons on rGO sheets has been confirmed by Transmission electron microscopy whereas XRD has confirmed the existence of rGO and MoS_2 through the presence of peaks corresponding to MoS_2 and graphene.

10. Copper based composites containing 2.0 wt. % rGO-MoS_2 hybrid nanoparticles could be successfully synthesized using spark plasma sintering. Raman spectroscopy confirmed the presence of rGO-MoS_2 particles, through the presence of D and G peaks of graphene oxide around 1350 and 1580 cm^{-1}, and E^1_{2g} and A_{1g} peaks corresponding to MoS_2 around 380 and 408 cm^{-1}.

11. The reinforcement of 2 wt. % rGO-MoS_2 hybrid results in a significant improvement in hardness and tensile strength of Copper and same has been attributed to the hindrance offered by the uniformly distributed of rGO-MoS_2 hybrid to the movement of dislocations *via* multidimensional interactions. The formation of hard MoC in the composites confirmed by X-ray diffraction has also contributed to the increase in hardness and tensile strength.

12. The hardness, density and tensile strength of the Cu-2 wt. % rGO-MoS_2 composites have been found to decrease with increasing sintering temperature from 600 to 750 ˚C and composite sintered at 600 ˚C has shown highest hardness, density and tensile strength which has been ascribed to the increase in tendency of agglomeration of reinforcing phase with increasing temperature and different coefficients of thermal expansion of constituents.

7.2.2 FRICTION AND WEAR CHARACTERISTICS OF Cu-2 wt. %rGO-MoS_2 COMPOSITES SINTERED AT DIFFERENT TEMPERATURES

13. Copper based composites containing 2 wt. % rGO-MoS_2 exhibit at least 3 times lower friction coefficient (~ 0.059) and 35 times low wear rate compared to pure copper, which has been ascribed to the relatively higher hardness of composites as compared to pure copper and the formation of tribo-layer over the worn surface of composites.

14. Both coefficient of friction and wear rate decrease with increasing sintering temperature from 600 to 700 °C followed by an increase till 750 °C. A decrease in both till 700 °C has been explained on the basis of the extent of the area coverage provided by the tribo-layer containing the lubricious graphene oxide and MoS_2 phases.

15. In plane expansion and contraction of graphene sheet with change in sintering temperature is observed, which is confirmed by the blue and red shift of G band peak position corresponding to graphene oxide from Raman spectroscopy analysis, this behavior is responsible for uniform and area coverage of tribo-layer formation, and it has been observed that in plane residual stress become tensile from compressive on increasing the sintering temperature up to 700 °C, further increasing the sintering temperature to 750 °C increase in compressive residual stress is observed, graphene provide the effective lubrication when it experience in-plane residual tensile stress attributed to high strength of graphene in tension as compared to compression.

16. The self-lubricating properties of rGO-MoS_2 hybrid, its transfer to the counterface and the formation of rGO-MoS_2 containing tribo-thin film on the counter surface are believed to have played a vital role in improving the tribological properties of composite in terms of reduced coefficient of friction and wear rate.

17. A mechanism based on the contraction and expansion of graphene skeleton in the Cu-rGO-MoS_2 composites as a function of sintering temperature and sliding stress has been proposed to elucidate the relative changes in the friction and wear behavior of such composites. The composite sintered at 700 °C has shown the optimum tribological performance while retaining a reasonable level of mechanical properties.

18. The wear mechanism associated with the Cu-2 wt. % rGO-MoS_2 composites sintered at different temperatures is found to be a combination of mild abrasion and adhesion under the condition of load and speed used in the present investigation.

7.2.3 FRICTION AND WEAR CHARACTERISTICS Cu-rGO, Cu-MoS_2 AND Cu-rGO-MoS_2 COMPOSITES

19. The decrease in friction and wear rate of Cu-rGO composite in comparison to pure copper for sliding against steel ball could be attributed to oxide layer formation over the worn track, which has been confirmed from elemental mapping of the worn track.

20. Composite Cu-rGO shows a gradually increasing friction coefficient which eventually meet the friction curve of pure copper around 6000 cycles, it could

be attributed to the fatigue wear, which has been confirmed by the furrows observed on worn track and facets in the subsurface region from SEM micrographs.

21. A significant decrease in the friction coefficient value (~0.22) and wear rate is observed for MoS_2 reinforced copper based composite as compared to pure copper and Cu-rGO reinforced composite, which could be attributed to formation of MoS_2 mixed tribo-oxide layer formation over the worn track.

22. The addition of rGO-MoS_2 in copper matrix reduce the coefficient of friction to 0.08 and minimum wear rate is observed which could be attributed to formation of tribo-oxide layer over the worn track and transfer layer over the counter face steel ball, which has been confirmed by the raman spectroscopy and elemental mapping, these passive layer formation inhibits the direct metal to metal contact, thus, reduction in friction and wear is observed.

23. Wear mechanism for pure copper sliding against the steel ball is the combination of abrasion and adhesion, whereas wear mechanism associated with rGO reinforced composite is fatigue wear and adhesion, while MoS_2 reinforced copper based composite exhibits minor abrasion and oxidation and composite Cu-rGO-MoS_2 exhibits negligible wear.

24. The friction and wear performance of (2 wt. %) rGO-MoS_2 reinforced composite has been found to be better than the composites containing either rGO or MoS_2 as stand-alone solid lubricants which reflects a probable synergy between rGO and MoS_2. Hence, it can be concluded that rGO-MoS_2 can be a promising and potential reinforcement for developing self-lubricating composites.

7.2.4 EFFECT OF rGO-MoS_2 CONTENT AND LOAD ON FRICTION AND WEAR BEHAVIOR OF COMPOSITES

25. Both hardness and density of Cu-rGO-MoS_2 composites have been found to decrease with increasing content of rGO-MoS_2 phase except for the composite containing 0.5 wt. % rGO-MoS_2 which has been attributed to the non-uniform distribution of the reinforcing phase in matrix.

26. The average coefficient of friction has been found to decrease with increasing content rGO-MoS_2 lubricating phase from 0.5 to 2.0 wt. %. The composite containing 0.5 wt. % rGO-MoS_2 has shown the largest coefficient of friction (~ 1.0) whereas the one containing 2.0 wt. % has the smallest (~0.2). It has been attributed to increase in rGO-MoS_2 lubricating phase.

27. A marginal increase in coefficient of friction has been observed with increasing load from 4 to 10 N. The composite CGM2.0, containing 2 wt. % rGO-MoS_2 has exhibited the minimum coefficient of friction (~0.2)**.**

28. The wear rate has been found to increase sharply with increase in rGO-MoS_2 content from 0.5 to 1 wt. % followed by a decrease with increase in the reinforcement content to 2 wt. %. This behavior could be attributed to crack formation resulted from the brittleness induced in composite with increase in rGO-MoS_2 content up to 1.0 wt.%, however, further increase the reinforcement content to 2.0 wt.%, tribo-layer formation occurs.

29. The wear rate has been found to increase significantly with increasing load for composites containing 1.0 and 1.5 wt. % of rGO-MoS_2. However, no significant increase in wear rate with increasing load has been observed for the composites containing 0.5 and 2 wt. % rGO-MoS_2 which has been attributed to formation of compact oxide layer over the surface of composite containing 0.5 wt.% rGO-MoS_2 and tribo-oxide layer over the composite containing 2.0 wt.% rGO-MoS_2.

30. The minimum wear rate shown by Cu-0.5 wt. % rGO-MoS_2 regardless in spite of showing the maximum coefficient of friction has been attributed to the formation of oxide layer over worn track and ductile nature of the composite, whereas the similar wear rate shown by Cu-2 wt. % rGO-MoS_2 composite has been attributed to the formation of a tribo- layer on the worn surfaces of composite and the ball slid against it.

31. The highest wear rate along with relatively high coefficient of friction observed for Cu-1.0 wt. % rGO-MoS_2 composite has been attributed to the fatigue spalling and combination of two and three body abrasion as confirmed by SEM examination of the worn surfaces of composite and counter face ball.

32. The prevailing wear mechanism is observed to be a combination of oxidation and adhesion for Cu-0.5 wt. % rGO-MoS_2 composite, whereas two and three body abrasion are the dominating wear mechanisms for Cu-1.0 wt. % rGO-MoS_2 and Cu-1.5 wt. % rGO-MoS_2 under the conditions of load and sliding speed used in the present study. However, mild abrasion has been observed to be the dominating mechanism of wear for Cu-2.0 wt. % rGO-MoS_2 composite.

FUTURE SCOPE

In the present study, tribological behavior of copper based hybrid composites containing a combination of hard (Al_2O_3) phase and solid lubricants MoS_2 and *h*-BN has been examined. Also, the potential of a hybrid rGO-MoS_2 phase has also been explored as a self-lubricating reinforcement in copper matrix and the results have indicated that it may be used as self-lubricating component. However, there are many possibilities to explore rGO-MoS_2 as the lubricating phase for variety of applications and sliding condition. Thus, the studies following investigations can be carried out in future to explore the friction and wear behavior of rGO-MoS_2 reinforced copper based composites.

1. Investigations on the high temperature (room temperature to 500 $^{\circ}$C) tribological behavior of Cu-rGO-MoS_2 under different loads and speeds.

2. A comparative study may also be carried out to explore the friction and wear behavior of copper based composites reinforced with rGO-MoS_2 hybrid and a combination of rGO and MoS_2 separately.

3. The tribological behavior of rGO-MoS_2 reinforced copper based composites can also be evaluated under electrically charged conditions.

4. The tribological behavior of rGO-MoS_2 reinforced composite under corrosive environments.