CHAPTER 6

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CONCLUSIONS

The study conducted on the synthesis of in-situ Ti-TiB composites containing different amounts of TiB by spark plasma sintering (SPS) as well as vacuum arc melting (VAM) and evaluation of their friction and wear behavior under dry sliding reciprocating conditions at different loads of 10, 15, 20, and 25 N and frequencies of (a) 5 Hz for spark plasma sintered Ti-TiB-Fe composites containing varying amount of Fe and boron and (b) 4, 7 Hz, 10 Hz and 15 Hz for composites prepared through VAM has led to certain salient conclusions which are presented below.

6.1 CHARACTERIZATION AND RECIPROCATING WEAR OF SPARK PLASMA SINTERED TiTiBFe COMPOSITES

(A) TiBFe composites containing 10, 20 and 30 at. % Fe and a fixed amount of Boron i.e., TiBFe1010, TiBFe1020 and TiB Fe1030

1. The *in-situ* Ti-TiB-Fe composites containing 10, 20 and 30 at.% Fe composites could be successfully synthesized via spark plasma sintering. In situ reaction between Ti, TiB_2 and Fe resulted in the formation of TiB and FeTi as confirmed by X-ray diffraction analysis.
2. All the composites i.e., TiBFe1010, TiBFe1020 and TiBFe1030 have been observed to possess a typical microstructure containing β-Ti, TiB and

intermetallic FeTi. The amount of FeTi increased whereas the size of TiB decreased i.e., became finer with increasing content of Fe reflecting thus the role of Fe in refining the size of TiB.

3. The hardness of the composites increased from 488 to 871 $HV_{0.1}$ with the addition of Fe from 10 to 30 at. %, which has been attributed to the increasing amount of the formation of FeTi, which is brittle and hard, and reduction in the size of TiB, which acts as the barrier to the movement of dislocations.
4. The coefficient of friction decreased with increasing amount of Fe at each of the loads i.e., 10, 15, 20 and 25 N and the composite containing 30 at. % Fe, i.e., TiBFe1030 showed the lowest coefficient of friction.
5. The variation of wear rate with respect to load did not show any particular trend. However, wear rate decreased with increasing Fe content from 10 to 20 at. % followed by an increase again for 30 at. % addition at each of the load. The lowest wear rate was observed for TiBFe1020 having 20 at. % Fe despite its lower hardness than TiBFe1030 and it has been attributed to dominating effect of the transfer layer of present over the sliding surface which shields the underlying substrate from direct metal-metal contact.
6. The dominating mechanisms of wear in the composites are observed to be plowing, abrasive, oxidation, and delamination under the sliding conditions used in the present study.

(B) TiBFe composites containing 10, 20 and 30 at. % Boron and a fixed amount of Fe i.e., TiBFe1010, TiBFe2010 and TiBFe3010

1. The in-situ Ti-TiB-Fe composites containing 10, 20 and 30 at.% B composites were successfully synthesized via spark plasma sintering. In situ reaction between Ti, TiB_2 and Fe resulted in the formation of TiB and FeTi as confirmed by X-ray diffraction analysis.

2. All the composites i.e., TiBFe1010, TiBFe2010 and TiBFe3010 have been found to consist of β-Ti, TiB and intermetallic FeTi. The hardness of the composites increased from 488 to 964 $HV_{0.1}$ with the addition of B from 10 to 30 at. %, due to the increased amount of TiB, which is brittle and hard.

3. The composite TiBFe3010 showed the lowest coefficient of friction (between 0.51 and 0.44) and wear rate (TiBFe3010) with increasing load (ranging from 0.41 - 1.32 x10 ^{4} mm^3/m) due to increasing TiB content.

4. The dominating mechanisms of wear have been found to be delamination and ploughing as revealed by morphologies of the worn surfaces.

4.2 RECIPROCATING WEAR OF COMPOSITES SYNTHESIZED VIA VACUUM ARC MELTING

6.2.1 Friction and Wear Under Different loads of 10, 15, 20 and 25 N and a Fixed frequency of 4 Hz

The tests conducted to explore the friction and wear characteristics of Ti, TiB50, TiB60, TiB70, TiB80, and TiB85 composites under different contact load of 10,15,20 and 25 N and a fixed sliding frequency of 4 Hz have resulted in following conclusions:

1. In-situ Ti-TiB composites containing different (50, 60, 70, 80, and 85) vol.% of TiB namely, TiB50, TiB60, TiB70, TiB80 and TiB85 have been successfully synthesized by a cost-effective vacuum arc melting process. The

morphology of TiB changed from needle-like whiskers to blocky structures with increasing content of TiB.

2. The porosity of composites has been found to decrease with increasing TiB content. The lowest porosity of 0.1 ± 0.2% is shown by TiB85 whereas the TiB50 showed the highest porosity 0.6 ± 0.7%. The hardness of the composites increased with increasing content of TiB from 50 to 85 vol. % due to the higher intrinsic hardness of TiB.

3. The variation of friction coefficient with time has been found to be smooth for Ti, TiB80, and TiB85 in comparison to TiB50, TiB60, and TiB70. TiB80 composite has shown the lowest coefficient of friction for the complete duration of sliding at all loads whereas pure Ti showed the highest.

4. Both the coefficient of friction and wear rate increased with increasing load for all the composites. At a given load, the coefficient of friction and the wear rate of the composites decreased from 50 to 60 Vo.% TiB followed by an increase for 70 Vol.% and a reduction thereafter till 80 vol.% and remained almost the same thereafter till 85 vol.% TiB.

5. The composite having 80 vol.% TiB showed the lowest coefficient of friction and wear rate among all the composites. The observed behavior has been explained on the basis of the formation of a transfer layer of wear debris over the surface, its degree of compaction and the presence of lubricious oxides (TiO_2, B_2O_3 and H_3BO_3) as revealed by XPS spectroscopy.

6. The operative mechanism of wear has been found to be a mixture of ploughing, adhesion and oxidation for pure Ti whereas the same for composites is adhesion, oxidation, delamination and abrasion.

6.2.2 Friction and Wear Under Different loads of 10, 15, 20 and 25 N and a Fixed frequency of 7 Hz

1. The variation of coefficient of friction with time has shown a fluctuating trend with relatively larger and similar amplitude of fluctuations during run-in period for pure Ti as well as composites, before being stabilized at a certain level. However, the amplitude has been found to decrease with increasing volume fraction of TiB in the composites.

2. The average coefficient of friction for Ti, TiB50, TiB60, TiB70, TiB80, and TiB85 composites has been found to decrease with increasing load with the exception of Ti, which has shown an increase in the coefficient of friction from 10 to 25 N. However, TiB80 has shown a lower COF at all the loads in comparison to TiB50, TiB60, TiB70, and TiB85 with a minimum COF of 0.40 and maximum COF of 0.51 at 10 N. The observed behavior has been attributed to the presence of a transfer layer of oxides of debris over the surface which prevents direct contact between mating bodies and provides easy shearing junctions at the interface.

3. The variation of wear rate with load did not show any particular trend in composites whereas it has been observed to increase with increasing load for pure Ti. The wear rate of TiB50 increased from 10 to 15 N then decreased to 25 N. TiB60 showed an increase in wear rate from 10 to 20 N and thereafter decreased a little at 25 N, while TiB70, TiB80, and TiB85 showed similar trends i.e. their wear rate increased from 10 N to 15 N followed by a decrease till 25 N with a minimum value of 0.18 x 10^{-4} mm^3/m.

4. TiB80 showed the lowest CoF and wear rate among all composites due to the formation of a well-compacted transfer layer that could not be detached during

sliding and shielded the underlying substrate from direct contact with the counter face apart from providing the low shearing oxide junctions. The formation of oxides has been confirmed by XRD.

5. The wear mechanism was found to be a combination of delamination, abrasion and oxidation among all composites whereas, for pure Ti it was mix of plastic deformation, ploughing and oxidation.

6.2.3 Friction and Wear Under Different loads of 10, 15, 20, and 25 N and a Fixed frequency of 10 Hz

1. Pure Ti showed a stable coefficient of friction with time for complete duration of the test while TiB50, TiB60, TiB70, TiB80, and TiB85 showed a highly fluctuating trend of variation of CoF with time during run-in period before being stabilized. The duration of run-in period was found to depend on the composition and the load.

2. The average coefficient of friction for pure Ti, TiB50, TiB60, TiB70, TiB80, and TiB85 decreased with increasing load from10 to 25 N. The composite TiB80 showed the lowest COF among all and pure Ti showed the highest.

3. The wear rate of pure Ti increased with increasing load Ti and it had the highest wear rate among all the materials. The composites did not reveal any specific trend of variation of wear rate with the load. Among all composites, TiB80 demonstrated the lowest wear rate and the observed behavior has been attributed to the presence of a transfer layer containing lubricious oxides as mentioned earlier.

4. The mechanism of wear is observed to be a combination of a ploughing, abrasion, and oxidation for Ti and whereas the same for composites was a mix of delamination, abrasion, adhesion, and oxidation.

6.2.4 Friction and Wear Under Different loads of 10, 15, 20, and 25 N and a Fixed frequency of 15 Hz

1. Pure Ti showed a stable variation of CoF with time with small fluctuations in amplitude at all the loads and almost no running period. However, composites showed larger fluctuations during running-in periods depending on the load and composition before attaining a steady state. appears to get stabilized

2. The average COF is found to increase with increasing load for pure Ti whereas it is observed to either decrease of remain constant for composites with increasing load. TiB80 showed the lowest coefficient of friction at all the loads. At relatively lower loads of 10 and 15 N pure Ti also showed almost same CoF as TiB80.

3. The wear rate did not show any specific trend of variation with load for at 15 Hz also. The wear rate decreased with an increase in load for TiB60, TiB80, and TiB85 whereas for TiB50 and TiB70 it decreased from 10 to 15 N followed by an increase at 20 N before decreasing further at 25 N. The wear rate shown by pure Ti is significantly higher in comparison to composites which reflects the effect of the addition of TiB,

4. Among all the composites, TiB85 composite has shown the lowest rate of wear at all the loads and the lowest rate of $0.23\times10^{-4} mm^3/m$ is observed at 25 N. This has been attributed to the formation of a well compacted transfer layer and its degree of compaction which prevents the wear of the underlying substrate.

5. The mechanism of wear for composite is a mixture of ploughing, abrasion, adhesion and oxidation whereas for Ti ploughing, delamination and oxidation are the primary mechanisms of wear.