

## List of figures

Fig. 1.1. Variation of strength with temperature for some engineering composites.....	5
Fig. 1.2. Various environmental details and testing methods used for the present investigation.....	8
Fig. 2.1. Crystal Structure of Graphite. ....	10
Fig. 2.2 Crystal Structure of Carbon Fibre. ....	11
Fig. 2.3. Variation of friction coefficient and wear rate with elastic modulus of carbon fibres in the frictional surface. ....	16
Fig. 2.4. Variation of percent weight loss of C/C composite sample with temperature in a gas mixture consisting of 79% He and 21% O <sub>2</sub> .....	17
Fig. 2.5. Variation of percent weight loss of C/C composites (with oxidation-inhibitor) with maximum specimen temperature.....	17
Fig. 2.6. Friction and wear properties of the two samples at various braking pressures: (a) temperature; (b) friction coefficient; (c) linear wear rate;(d) mass loss.....	19
Fig. 2.7. Comparison of the engagement conditions for each of the nanoadditive samples to the baseline plain C/C composite.....	20
Fig. 2.8. Variation of (a) friction coefficient and temperature with braking time at braking pressure of 0.6 MPa and brake speed of 25 m/s, and (b) maximum temperature with brake pressure at brake speed of 25 m/s....	21
Fig. 2.9. Variation of average friction coefficient with brake speed at the brake pressure of 0.6 MPa.....	22
Fig. 2.10. Variation of percentage of wear loss with oxidation temperature of C/C and CNF-C/C composite .....	24
Fig. 2.11. Variation of residual mass percentage with oxidation time at 1200 0C in air (C1; SiC coating, C2; CNT–SiC coating, C3; CNT–PyC5–SiC coating, C4; CNT–PyC10–SiC coating, C5; CNT–PyC15–SiC coating).....	25
Fig. 2.12. Variation of percentage weight loss with oxidation time of coated C/C composites in air at 1773 K .....	26
Fig. 2.13. Variation of friction coefficient with sliding time for the CG coating (SiC coating without Ti powder) and the FG coating (SiC coating with small amounts of Ti powder) at 600°C .....	27

Fig. 2.14. Variation of friction coefficient with time of ceramic filler modified C/C composites at 25 m/s: (a) CCSSF (C/C composite with small-sized SiC filler), (b) CCSBF (C/C composite with small-sized B <sub>4</sub> C filler), (c) CCLSF (C/C composite with large-sized SiC filler), and (d) CCLBF (C/C composite with large-sized B <sub>4</sub> C filler) ....	28
Fig. 2.15. Radial profiles of the friction track of both opposing discs after friction at (a) low temperature and (b) high temperature (OM images taken between crossed polarizers with addition of a retarder plate).....	30
Fig. 2.16. Emergency brake system (left) and internally ventilated brake disk for passenger cars (right), made of C/C-SiC composite.....	36
Fig. 2.17. Variation of friction coefficient with number of brakings under the Influence of the pad material on the frictional behaviour of 2D reinforced C/C-SiC brake disks.	37
Fig. 2.18. Variation of wear rates of C/C-SiC brake disks in combination with commercial lining materials .....	38
Fig. 2.19. Dependence of friction properties of C/C - SiC composites on the content of pyrolytic carbon in matrix. (a) Average friction coefficient; (b) braking time; (c) weight wear rate.....	39
Fig. 2.20. Variation of friction coefficient with time for samples from different methods (a) PIP; (b) CVI.....	40
Fig. 2.21. Variation of percent porosity with weight percentage of SiC content (a) PIP; (b) CVI.....	41
Fig. 2.22. Variation of friction coefficient with weight percentage of SiC content for different samples (a) PIP; (b) CVI.....	42
Fig. 2.23. The effect of braking pressure and braking speed on the average friction coefficient of C/SiC brake materials.....	43
Fig. 2.24. Schematic illustration of the debris filled and the friction film formed. ....	44
Fig. 2.25. The effect of braking pressure and braking speed on the wear rate of C/SiC brake materials.....	44
Fig. 2.26. First braking curves of C/C-SiC on different condition: (a) Dry condition; (b) Wet condition.....	45
Fig. 2.27. The curve of friction coefficient of samples as a function of braking time (a, without graphitization; b, with graphitization) .....	47
Fig. 2.28. Friction coefficient as a function of number of braking tests (A, without graphitization; B, with graphitization).....	49

Fig. 2.29. Friction and wear properties in dry conditions: (a) Kinetic and static friction coefficient, (b) Typical brake curves, (c) Linear wear rates. ....	50
Fig. 3.1. Processing of C/C and C/C-SiC composites. ....	55
Fig. 3.2. Schematic showing (a) composite pin with normal orientation of laminates, and representative wear mechanisms in (b) normal (NL) and (c) anti-parallel (APL) direction of fibres.....	57
Fig. 3.3. Schematic showing (a) composite pin with parallel orientation of laminates, (b) representative wear mechanisms in parallel (PL) direction of fibres, and (c) grit abrasion.....	58
Fig. 3.4. Representative plot for variation of friction coefficient with time plotted for 40 N load and 2 m/s sliding velocity with normal orientation of laminates (a) C/C composites, (b) C/C – SiC composites .....	61
Fig. 3.5. Representative plot for variation of friction coefficient with time plotted for 20 N load and 2 m/s sliding velocity with parallel orientation of laminates (a) C/C composites, (b) C/C – SiC composites. ....	62
Fig. 3.6. Variation of friction coefficient with normal load for low conformity contacts of C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites. ....	63
Fig. 3.7. Variation of friction coefficient with sliding velocity for low conformity contacts of C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites. ....	63
Fig. 3.8. Variation of friction coefficient with normal load for non-conformal hertzian contacts of C/C and C/C-SiC disks.....	64
Fig. 3.9. Variation of friction coefficient with sliding velocity for non-conformal hertzian contacts of C/C and C/C-SiC disks.....	65
Fig. 3.10. Variation of wear loss with load for low conformity contacts of C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites. ....	65
Fig. 3.11. Variation of wear loss with sliding velocity for low conformity contacts of C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites.....	66
Fig. 3.12. Variation of wear loss with load for non-conformal hertzian contacts of C/C and C/C-SiC disks.....	67
Fig. 3.13. Variation of wear loss with sliding velocity for non-conformal hertzian contacts of C/C and C/C-SiC disks.....	67
Fig. 3.14. Fig. 3.14. SEM images showing C/C normal tested at (a) 40 N load and 2 m/s sliding velocity, and (b) 20 N load and 3 m/s sliding velocity. ....	68

Fig. 3.15. SEM images showing C/C parallel tested at (a) 60 N load and 2 m/s sliding velocity, and (b) 20 N load and 2.5 m/s velocity.....	69
Fig. 3.16. SEM images showing composites tested at 30 N load and 2 m/s sliding velocity (a) C/C-SiC normal, (b) C/C-SiC parallel.....	71
Fig. 3.17. SEM images showing (a) C/C-SiC normal tested at 3m/s sliding velocity and 20 N load, and (b) C/C-SiC parallel tested at 1.5 m/s sliding velocity and 20 N load. ..	72
Fig. 3.18. SEM images showing composites tested at 40 N load and 2 m/s sliding velocity (a) C/C disk, and (b) C/C-SiC disk. ....	74
Fig. 3.19. A representative plot for variation of friction coefficient with time for C/C composites (plotted for 70 N load).. ....	75
Fig. 3.20. A representative plot for variation of friction coefficient with time for C/C-SiC composites (plotted for 70 N load).. ....	75
Fig. 3.21. A representative plot for variation of friction coefficient with time for C/C and C/C-SiC composites in non-conformal hertzian contacts (plotted for 70 N load)... ..	76
Fig. 3.22. Variation of friction coefficient with normal load of C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites.....	77
Fig. 3.23. Variation of friction coefficient with normal load in non-conformal hertzian contacts for C/C and C/C-SiC plate.....	77
Fig. 3.24. Variation of wear loss with normal load of C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites.....	78
Fig. 3.25. Variation of wear loss with normal load in non-conformal hertzian contacts for C/C and C/C-SiC plate. ....	79
Fig. 3.26. SEM images showing composites tested at 70 N normal load (a) C/C normal, and (b) C/C-SiC normal.....	80
Fig. 3.27. SEM images showing (a) C/C parallel tested at 80 N, and (b) C/C-SiC parallel tested at 70 N.. ....	81
Fig. 3.28. SEM images showing composite tested at 70 N in non-conformal hertzian contacts (a) C/C composite, and (b) C/C-SiC composite.. ....	83
Fig. 4.1. Percentage increase of weight for different orientation of laminates after immersing in brake oil. ....	90
Fig. 4.2. Average decay rate of friction coefficient in brake oil condition.....	91
Fig. 4.3. Representative plot for variation of friction coefficient with time plotted for 40 N load and 2 m/s sliding velocity with normal orientation of laminates (a) C/C composites, (b) C/C – SiC composites. ....	92

Fig. 4.4. Representative plot for variation of friction coefficient with time plotted for 40 N load and 2 m/s sliding velocity with parallel orientation of laminates (a) C/C composites, (b) C/C – SiC composites. ....	93
Fig. 4.5. Variation of friction coefficient with normal load at 2 m/s sliding velocity for C/C normal, C/C parallel, C/C-SiC normal, and C/C-SiC parallel.....	94
Fig. 4.6. Variation of friction coefficient with sliding velocity at 20 N load for C/C normal, C/C parallel, C/C-SiC normal, and C/C-SiC parallel.....	94
Fig. 4.7. Variation of friction coefficient with normal load at 2 m/s sliding velocity in non-conformal Hertzian contacts for C/C and C/C-SiC disks.....	95
Fig. 4.8. Variation of friction coefficient with sliding velocity at 20 N load in non-conformal Hertzian contacts for C/C and C/C-SiC disks.....	96
Fig. 4.9. Variation of wear loss with normal load at 2 m/s sliding velocity for C/C normal, C/C parallel, C/C-SiC normal, and C/C-SiC parallel.....	97
Fig. 4.10. Variation of wear loss with sliding velocity at 20 N load for C/C normal, C/C parallel, C/C-SiC normal, and C/C-SiC parallel.....	97
Fig. 4.11. Variation of wear loss with normal load at 2 m/s sliding velocity in non-conformal Hertzian contacts for C/C and C/C-SiC disks.....	98
Fig. 4.12. Variation of wear loss with sliding velocity at 20 N load in non-conformal Hertzian contacts for C/C and C/C-SiC disks.....	98
Fig. 4.13 SEM images showing (a) brittle fracture of matrix in C/C normal tested at 30 N load and 2 m/s velocity, and (b) fibre fracture in C/C normal tested at 50 N load and 2 m/s velocity.....	100
Fig. 4.14. SEM images showing (a) fibre fragment in wear debris of C/C parallel tested at 40 N load and 2 m/s sliding velocity, and (b) SiC particles in C/C- SiC normal tested at 40 N load and 2 m/s sliding velocity.....	102
Fig. 4. 15. SEM images showing (a) C/C disk, and (b) C/C-SiC disk tested at 50 N load and 2 m/s sliding velocity.....	102
Fig. 4.16. EDX spectrum of C/C-SiC disk tested at 30 N load and 2 m/s velocity.....	103
Fig. 4.17. SEM images showing C/C composites tested at 2.5 m/s velocity and 20 N load (a) C/C normal, and (b) C/C parallel.....	104
Fig. 4.18. SEM images showing C/C-SiC composites tested at 2.5 m/s sliding velocity and 20 N load (a) C/C-SiC normal, (b) C/C-SiC parallel.....	105
Fig. 4.19. SEM images showing (a) C/C disk tested at 3 m/s sliding velocity and 20 N load, and (b) C/C-SiC disk tested at 2.5 m/s sliding velocity and 20 N load.....	105

Fig. 4. 20. Representative plot for variation of friction coefficient with time at 70 N load in (a) C/C composites and (b) C/C – SiC composites tested in low conformity contacts and, (c) C/C and C/C-SiC composites tested in non-conformal hertzian contacts.....	109
Fig. 4.21. Variation of friction coefficient with normal load in low conformity contacts for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites.....	110
Fig. 4.22. Variation of friction coefficient with load in non-conformal hertzian contacts for C/C and C/C-SiC plate.....	111
Fig. 4.23. Variation of wear loss with normal load in low conformity contacts for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites.....	111
Fig. 4.24. Variation of wear loss with normal load in non-conformal hertzian contacts for C/C and C/C-SiC plate.....	112
Fig. 4.25. SEM images showing composites tested at 80 N load (a) C/C normal, and (b) C/C-SiC normal.....	115
Fig. 4.26. SEM images showing (a) C/C parallel tested at 70 N load, (b) C/C-SiC parallel tested at 90 N load.....	116
Fig. 4.27. SEM images showing composites tested in non-conformal hertzian contacts (a) C/C plate tested at 80 N load, and (b) C/C-SiC plate tested at 70 N load.....	118
Fig. 5.1. Variation of friction coefficient with normal load for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.....	124
Fig. 5.2. Variation of friction coefficient with sliding velocity for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.....	125
Fig. 5.3. Variation of friction coefficient with normal load in non-conformal hertzian contacts for C/C and C/C-SiC disks.....	125
Fig. 5.4. Variation of friction coefficient with sliding velocity in case of non-conformal hertzian contacts for C/C and C/C-SiC disks.....	126
Fig. 5.5. Variation of wear loss with normal load for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.....	127
Fig. 5.6. Variation of wear loss with sliding velocity for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.....	128
Fig. 5.7. Variation of wear loss with load for non-conformal hertzian contacts for C/C and C/C-SiC disks.....	128
Fig. 5.8. Variation of wear loss with sliding velocity for non-conformal hertzian contacts for C/C and C/C-SiC disks.....	129

Fig. 5.9. SEM images showing (a) Compacted wear debris and oxide layer in C/C normal tested at 40 N load, and (b) Cracks parallel to the laminates and fibre fragments in C/C normal tested at 50 N load.....	130
Fig. 5.10. SEM images showing C/C parallel tested at (a) 20 N load, and (b) 40 N load.....	131
Fig. 5.11. SEM images showing C/C-SiC normal tested at (a) 40 N load, and (b) 50 N load.....	133
Fig. 5.12. SEM images showing C/C-SiC parallel tested at (a) 40 N load, and (b) 50 N load.....	133
Fig. 5.13. SEM images showing C/C normal tested at (a) 2 m/s sliding velocity, and (b) 3 m/s sliding velocity.....	134
Fig. 5.14. SEM images showing C/C-SiC normal tested at (a) 2 m/s sliding velocity, and (b) 2.5 m/s sliding velocity .....	135
Fig. 5.15. SEM image showing C/C parallel tested at 1.5 m/s sliding velocity .....	136
Fig. 5.16. SEM images showing C/C-SiC parallel tested at (a) 2 m/s sliding velocity, and (b) 2.5 m/s sliding velocity .....	137
Fig. 5.17. SEM images showing C/C composite in non-conformal hertzian contacts tested at (a) 40 N load and 2 m/s sliding velocity, and (b) 20 N load and 3 m/s sliding velocity.....	138
Fig. 5.18. SEM images showing (a) Cracks due to thermal mismatch in C/C parallel tested at 30 N, and (b) Delamination pits in C/C parallel tested at 60 N.....	141
Fig. 5.19. Variation of friction coefficient with normal load in low conformity contacts for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel.....	143
Fig. 5.20. Variation of friction coefficient with normal load in non-conformal Hertzian conformity contacts for C/C and C/C-SiC plate .....	143
Fig. 5.21. Variation of friction coefficient with load in low conformity contacts for C/C normal, C/C parallel, C/C-SiC normal and C/C-SiC parallel composites .....	144
Fig. 5.22. Variation of friction coefficient with load in non-conformal Hertzian conformity contacts for C/C and C/C-SiC plates.....	145
Fig. 5.23. SEM images showing C/C normal tested at (a) 60 N load, and (b) 70 N load.....	146
Fig. 5.24. SEM images showing C/C parallel tested at (a) 60 N load, and (b) 70 N load.....	147

Fig. 5.25. SEM images showing C/C-SiC normal tested at (a) 70 N load, and (b) 80 N load.....	148
Fig. 5.26. SEM image showing C/C-SiC parallel at 70 N load. ....	148
Fig. 6.1. Variation of friction coefficient with time in case of normal/parallel combination of laminated composites (at 80N load). ....	154
Fig. 6.2. Variation of friction coefficient with normal load in case of normal orientation of laminated composites. ....	155
Fig. 6.3. Variation of wear loss of pin (normal orientation) with normal load.....	156
Fig. 6.4. Variation of wear loss of parallel plate (pin having normal orientation) with normal load .....	156
Fig. 6.5. Variation of friction coefficient with time in case of parallel/parallel combination of laminated composites (at 80N load). ....	157
Fig. 6.6. Variation of friction coefficient with normal load in case of parallel orientation of laminated composites .....	158
Fig. 6.7. Variation of wear loss of pin (parallel orientation) with normal load.....	159
Fig. 6.8. Variation of wear loss of parallel plate (pin having parallel orientation) with normal load.. ....	159
Fig. 6.9. SEM images showing (a) discontinuous friction film in C/C normal pin tested with C/C parallel plate at 80 N load, and (b) C/C normal pin tested with C/C-SiC parallel plate at 80 N.....	161
Fig. 6.10. SEM images showing (a) ejected SiC particles and formed friction film in C/C-SiC normal pin tested with C/C-SiC parallel plate at 80 N load, and (b) friction film and fibre fragments in wear debris of C/C parallel pin tested with C/C parallel plate at 80 N load.....	163
Fig. 6.11. SEM images showing (a) fibre fragments and cracks in C/C parallel pin tested with C/C-SiC parallel plate tested at 70 N load, and (b) fibre breakage sites in C/C-SiC parallel pin tested with C/C-SiC parallel plate tested at 70 N load.....	165
Fig. 7.1. Bar diagram showing variation of friction coefficient with orientation of laminates and conformity conditions for unidirectional and reciprocating sliding under dry environment.....	169
Fig. 7.2. Bar diagram showing variation of wear loss with orientation of laminates and conformity conditions for unidirectional and reciprocating sliding under dry environment.. ....	170

Fig. 7.3. Bar diagram showing variation of friction coefficient with orientation of laminates and conformity conditions for unidirectional and reciprocating sliding under brake oil environment..	171
Fig. 7.4. Bar diagram showing variation of wear loss with orientation of laminates and conformity conditions for unidirectional and reciprocating sliding under brake oil environment..	172
Fig. 7.5. Bar diagram showing variation of friction coefficient with orientation of laminates and conformity conditions for unidirectional and reciprocating sliding under freezing environment..	173
Fig. 7.6. Bar diagram showing variation of wear loss with orientation of laminates and conformity conditions for unidirectional and reciprocating sliding under freezing environment..	174
Fig. 7.7. Bar diagram showing variation of friction coefficient among all environments for different orientation of laminates and conformity conditions in unidirectional sliding.....	175
Fig. 7.8. Bar diagram showing variation of wear loss among all environments for different orientation of laminates and conformity conditions in unidirectional sliding.....	175
Fig. 7.9. Bar diagram showing variation of friction coefficient among all environments for different orientation of laminates and conformity conditions in reciprocating sliding.....	176
Fig. 7.10. Bar diagram showing variation of friction coefficient among all environments for different orientation of laminates and conformity conditions in reciprocating sliding.....	177
Fig. 9.1. Longitudinal fibre composite in contact with uniphase material 1..	184
Fig. 9.2. Parallel fibre composite in contact with uniphase material 2.....	187
Fig. 9.3. Friction coefficient of CFRE composite against epoxy with varying volume fraction of fibres (Present analysis)..	191
Fig. 9.4. Friction coefficient of carbon fibre reinforced epoxy composite against steel with varying volume fraction of fibres (Present analysis).....	191
Fig. 9.5. Experimental results of friction coefficients of carbon fibre reinforced epoxy composite against epoxy and steel with varying volume fraction of fibres.....	192