Friction, Fretting and Wear: Emerging Materials and Technologies

FOREWORD

Engineering design and analysis symbolizing artistic imagination and scientific intelligence are the drivers of modern technology. Extremely stringent specifications pertaining to dimensional accuracy and surface texture have provided tremendous impetus for the application and appreciation of surface science and contact mechanics. Reducing friction and wear between moving parts is a major aspect of fuel efficient design while at the same time ensuring safety and integrity of contacting components vulnerable to fretting wear, erosion, galling, scuffing and damage. Though these issues have been discussed and analysed extensively for well over two centuries, clear design guidelines to combat friction, fatigue and wear of metals, alloys and polymers continue to challenge scientists and engineers.

Friction, fracture and fatigue control the state of matter in the universe and therefore life. Although the origin and need for life to evolve on our planet remain unclear, the dominating role of friction, fracture and fatigue for creating, controlling and sustaining geological, biological and technological diversity is abundantly and ubiquitously evident around us. Geologically, the origin of continents, islands and volcanoes is attributed to the fracture and fragmentation of terrestrial crust; biological diversity is displayed by geckos darting across smooth walls and high ceilings while intelligent humans continue to slip and fall on rough floors; and, finally, marvellous technological diversity of emerging materials in the new millennium demonstrates exciting advances in micro/nanoengineering. The diversity of applications ranging from pharmaceuticals, dental implants, mining, transportation, space and nuclear medicine underlines the success of rigorous science and engineering education that prevailed almost until the beginning of the new millennium.

The enigma of friction has occupied human thought since the early dawn of civilization. The saga of ancient scientists, engineers and artisans to control and conquer friction in moving parts continues to this day with components shrinking in size but delivering more power. Along with fracture and fatigue the problem becomes even more enigmatic inasmuch as a comprehensive understanding of irreversible dissipative phenomena like friction, fracture, fatigue and turbulence requires fusing together irreconcilably complex concepts of classical and statistical thermodynamics. At this juncture, it is interesting to witness a delightful interaction and interplay of precepts and concepts underpinning seismology and tribology. Modelling friction in triggering tectonic events remains hugely challenging in spite of extensive field observations and numerical effort. Asperities hold the key to opening the doors into the mysterious phenomena of stick and slip between sliding blocks ranging from the submicroscopic to the tectonic scale spanning hundreds of kilometres. Depending upon the hardness and heterogeneity of asperities, the sliding blocks tangle, jerk, slide and rub their way around like a pair of sumo wrestlers. In a dizzy little earthquake paperback stirring up a cocktail of fact, myth, grapevine and anectode, the author Hough (2005) writes: Friction is another notorious geophysical hedgehog (probably inspired by Lewis Carroll). It is quite plausible that sliding blocks that are temporarily locked by asperities begin to move when they are deasperated.

Bridging classical and statistical concepts involves integrating over ten orders of magnitude in time and space in order to capture the rich diversity of fundamental effects entailing electronic transition, acoustic emission, dislocation dynamics and lattice vibration to mention a few. The role of phonons and electrons in reducing friction (Krim 2002) in monolayers appears as esoteric as the emission of electrons and photons in fracturing rocks while the role of fatigue and cavitation in weakening our bones through osteoporosis is simply taken for granted. Fractoemission (FE) of electrons accompanying brittle fracture of rocks became a sensational topic attracting diverse opinion among earthquake experts for a couple of decades culminating in the publication of an entire volume in the journal *Geophysical Research Letters* in 1996 (Hough 2005). The seemingly impenetrable interface between materials science and mechanics has driven away theoreticians to seek their fortune in experiment and simulation. The range of products, instruments and techniques to probe into the finer states of matter to achieve near-zero temperature, vacuum and atomic scale resolution is indeed devastating. There are exciting developments in molecular models to engineer MEMS and NEMS devices. While there is no doubt that science is turning nano, solids and structures continue to succumb to creep, corrosion and cavitation aggravated by heat, vibration and radiation. These issues have been recently addressed and compiled in a gigantic 10 volume, 130 chapter, 5000 page handbook edited by Ritchie & Murrakami (2003) entitled *Comprehensive structural integrity* cobbling together the ideas of 193 aerospace, biomechanical, chemical, civil, electrical, mechanical, metallurgical engineers and scientists from universities and industries drawn from 21 countries.

This special issue of *SĀDHANĀ* is an outcome of the editors' desire to promote students and young researchers working in the areas of friction, wear, emergent materials, fretting, AE and allied topics. The Internet era has vastly expanded the scope for acquiring new knowledge leaving little time for students to discover the joy of learning by integrating and interpreting conflicting results. Intelligence, interest and integrity of great scientists and engineers inspired the establishment of schools, colleges, universities and societies for promoting texts and student-friendly journals. Scientific and technical publications appear to be increasingly becoming monotonous owing to the excessive use of jargon and technological acronyms unfamiliar to students and junior researchers. Fortunately, the number of young and interested researchers actively engaged in experimental, theoretical and numerical modelling of the mechanical behaviour of solids subjected to erosion, abrasion, fretting, fatigue, impact and wear caused by mechanical, electrical, thermal and magnetic stimuli is steadily growing in recent years. Although we have come a long way in our journey towards designing that ever-elusive ideal material immune to the insidious effects of friction, fracture, fatigue, creep, corrosion and cavitation under the action of thermal, magnetic and nuclear radiation, there is plenty of room for exciting innovation for future generation of research students and budding inventors. This collection contains peer reviewed but unpublished articles, research theses results and new concepts for characterizing surface texture.

The special issue begins with a couple of papers by Menezes *et al* on roughness parameters and subsurface deformation in sliding contact. Surface texture is a complex concept demanding a rational tribomorphological assessment of the varying features of microscopic hills and valleys in addition to their compositional properties. In this context the *Del a* parameter appears to provide useful guidelines. The extent of subsurface plasticity and strain localization in Cu pins slid against steel plates revealed by scanning electron micrographs also point towards the paramount role played by texture. This is followed by a paper of Simha *et al* on anisotropic texture either introduced deliberately or developed during service. The authors examine the friction coefficient as a tensor quantity. This issue is of fundamental significance in the synthesis of surfaces, interfaces, thin films and coatings to enhance the life and performance of internal combustion engines, artificial hip and knee implants and computer hard disks from the viewpoint of exploiting elastic, thermal and tribological anisotropy. Surface engineering science and mechanics of texture constitute a critical part of designing MEMS and NEMS devices, as highlighted in a recent text by Freund & Suresh (2006). Shankara *et al* study solid lubrication with MoS_2 for space applications assessing zirconia and graphite for their potential as additive materials for high temperature operation (200°C).

Anantheshwara *et al* present the design, development and testing of an inertial slider for micropositioning over a span of several millimetres. They demonstrate the role of friction coefficient on the step size ranging from a few tens to a few hundreds of nanometres. The inertial sliding is controlled by alternating episodes of stick and slip whose magnitudes are in turn controlled by the inertial mass positioned on a tripod of sapphire balls attached to a piezoceramic plate. Mathew *et al* exploit acoustic emission (AE) for monitoring tool wear in face milling. AE signals in the range of 30 KHz–2 MHz were recorded for correlating with flank wear of the milling tool with just one uncoated carbide insert, and with two or three inserts. AE technology has its counterpart in seismology for measuring foreshocks and strong ground motion except that the earthquake sensors operate in the range of 0.1–10 Hz. It is possible to invert ground motion records to reconstruct the spatio-temporal sequence of terrestrial fracture events occurring along hundreds of kilometres of deep underground faults fracturing at speeds exceeding thousands of metres per second.

The following three papers address materials science and technology aspects pertaining to microstructure, hardness and orientation in a high temperature titanium alloy for aviation, nickel coated copper plate/tin–silver solder interface for printed circuit boards in microelectronics and carbon fibre reinforced plastic laminates to strengthen steel structures. Kuruvilla *et al* study a rolled Ti-Al-V-Fe-O_2 alloy to explore the role of longitudinal and transverse grain orientation on hardness and tensile properties, and conclude that the alloy has adequate ductility for mechanical working operations. Lin *et al* highlight the complex interfacial structure of Sn-3.5Ag solder bumps on nickel-coated Cu plates aged at 150°C for up to 96 hours. Backscattered SEM and EDS techniques unveil the presence of Sn–Cu–Co intermetallics in the interfacial layer. The thickening intermetallic layer with aging time develops microcracks coalescing eventually into a macroscopic crack after 96 hours. Patnaik *et al* present the intrinsic advantages of fibre reinforced plastic (FRP) strengthening steel plate, beam and shell structures citing the aging highways and bridges in the United States built largely in the 1950s and 1960s. The situation becomes more sober with regard to bridges and dams built in regions with seismicity. Only very recently (14 June 2008), the Bailey bridge over the river Beas linking Bhunter with Kullu bypass (NH21) in Himachal Pradesh, India, collapsed under a 50T trailer. This was an entirely unnecessary tragedy. This bridge supposedly designed for 15T maximum load highlights the critical need for installing advance warning systems for monitoring and maintaining public facilities. Adhesively bonded FRP laminates in conjunction with embedded AE sensors seem to offer viable *in situ* solutions provided that the laminates are protected against brittle catastrophic failure by interfacial crack propagation.

This special issue concludes with a quartet of papers by Ramesh *et al* addressing axisymmetric fretting in homogeneous and coated cylinders including micro and macro contact mechanics aspects for interacting asperities and axial wave propagation. The fretting analysis is mainly focussed on surface and near surface stress analysis for some prescribed combinations of normal and shear tractions. The axisymmetric Love stress functions in conjunction with fourier transforms are utilized for analysis. The ensuing results are compared with approximate predictions from 2D Airy stress functions. The formulation is continued for a coated cylinder to highlight the role of elastic moduli mismatch, coefficient of friction and loading configuration. It is shown that a softer coating leads to larger stresses in the substrate core while a harder coating reverses the trend. Hard coatings also bend considerably which is undesirable. The fretting phenomenon is intimately related to the interaction of asperities in the stick and slip zones along the contact. Only the macroscopic dimensional undulations are of importance in the contact zone whereas the microscopic asperities control the nature of frictional sliding in the slip zone. This forms the motivation for a photoelastic visualization of the stress field under interacting asperities. The final thirteenth paper extends the classic analysis due to Pochhammer in 1876 to a coated solid cylinder to help develop a simple rule-of-mixture approach for predicting the phase velocity in the first mode. The results of the analysis are useful for dynamic fretting analysis to help evolve accelerated fretting fatigue experiments. High cycle fatigue in general and fretting in particular demand advanced analytical as well as statistical design tools.

A remark in the preface of a text first published in 1993 (Hills *et al* 1993) on the mechanics of elastic contacts reads, ‘It might be argued that in the days when finite element methods are available to provide the solution to any linear elasticity problem this book is an anachronism. But contact problems, particularly those involving friction, are notoriously awkward to solve by finite elements, and the clarity of the picture provided by a finite element solution may not be as good as that provided by what is probably an exact answer to an idealization of the real problem, and which gives the opportunity for real physical insight’. The intervening period of 15 years has further accentuated the need for analytical insight into contact phenomena notwithstanding the inexorable deluge of finite element solutions inundating journals dealing with solids and structures. Thus, this special issue captures the challenges faced in advancing our understanding of friction, fatigue and fracture in the context of *emerging materials and technologies* focussing on microstructure, mechanical characterization, mathematical analysis, failure analysis and technological solutions.

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References

Krim J 2002 Surface science and the atomic-scale origins of friction: What once was old is new again. *Surface Science* 500: 741–758

Freund L B, Suresh S 2006 *Thin film materials* Cambridge University Press

Rithcie R O and Murakami Y (eds.) 2003, *Comprehensive structural integrity* Elsevier, Pergamon Press

Hough S E 2005 *Earthshaking science*: What we know (and don't know) about earthquakes Universities Press, Hyderabad

Hills D A, Nowell D, Sackfield A 1993 *Mechanics of elastic contacts* Butterworth-Heinemann Ltd.