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A review on tribology of surfaces and interfaces

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ABSTRACT

Tribological study includes surface interaction and mechanism involve between contacts. At contact points, surface forces affect the geometry and properties of material whereas stress concentration affects processes that involve during friction interactions. Nanomechanical behaviour of thin-film and surfaces has been largely studied during past years in the field of electronics industry such as microelectronics, optoelectronics application, aerospace industry, iron and steel industries and also adapted in the field of biological sector that likely to grow in near future extensively. High resolution microscope and computational techniques enable the material to investigate their interfacial problems at nanoscale. In this, we studied mechanism of tribology, with different deposition technique and their mechanical properties. Copyright © 2014 VBRI press.

Keywords: Tribology; contact mechanics; friction; wear.

Contents

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Introduction

Tribology and surface engineering

Tribology focuses on wear, friction and lubrication of two interacting surfaces in relative motion, it derived from Greek word ‘tribos’ meaning rubbing or sliding. Significance of tribology incorporated many years ago, the word introduced in 1966 **[1-2]**. Use of bearing since Stone Age (AD 40) reported by Davidson in 1957 **[3]**, use of a sledge by Egyptians in 1880 BC, wheels in 3500 BC **[4]**. Tribology first reported in Material wastage due to wear is the main cause for loss of mechanical performance which increases economy loss. Tribology combines many streams of study that includes physics, chemistry, mechanics, thermal, and materials science etc. Better understanding of tribology gives economical balance to the nation because due to increment in friction value gives rise in wear that directly affects the amount of material loss **[5-6]**. Surface interaction plays a vital role in tribology, interfacial characteristic of surfaces needs proper attention for better prospective of tribology. Tribology application includes from small-scale industries to heavy earth moving machinery to space. The advantage of the present field includes in various application such as diamond like carbon coatings **[7]**, physical vapour deposition coating **[8, 9]** ionic liquids **[10]**, surfactant in interface **[11]**, ceramic coating **[12]**, nano composite coatings **[13,14]**, bio-films **[15]** and lubricant additive **[16]**.

Friction and wear properties of material depend on the surface and its topography; due to surface interaction these properties may change **[17]**. Size of the particles, morphology, and structure of wear particles at interface are very important to study surface phenomena. In order to study surface at atomic scale new tools are available such as Auger electron spectroscopy (AES), x-ray photon electron spectroscopy (XPS), scanning ion spectroscopy and ion scattering spectroscopy, scanning electron microscope (SEM) and micro-probe analysis **[18,19]**. The topography of a surface (**Fig. 1**) made up of a lay, waviness and surface roughness. Surface roughness refers to high frequency irregularities on the surface caused by interaction of material and cutting tool whereas, waviness refers to low-frequency irregularities on the surface, caused by instability of the cutting tool. Lay is the machining pattern of the surface it may be parallel, circular, or multi directional. Surface measurement should be made perpendicular to direction of the lay **[20]**.

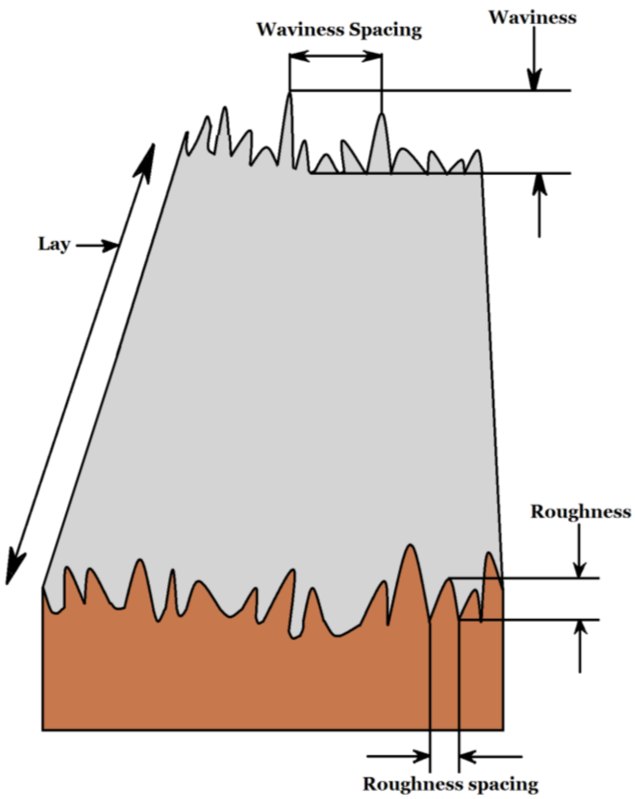

Fig. 1. Schematic diagram of surface roughness and waviness **[20]**.

Friction, wear and lubrication

When two body moves tangentially over another, which is in contact an unknown force is exerted to oppose motion of the body, known as friction. Coefficient of friction is the tangential force F to the normal load L on the contact i.e. $\mu = F/L$. Scientific word 'friction' first suggested by Leonardo Da Vinci (1452-1519), after that Guillaume Amontons rediscovered the two friction rules. Later on Charles-Augustin Coulomb added a third rule of friction **[21-22]** According to friction rule:

- Friction force is directly proportional to the normal load.
- Friction force does not depend on the apparent area of contact.
- Friction force is independent of velocity.

Sliding contact affects the friction behaviour, and time dependency of friction (**Fig. 2**) **[23]**. A sliding contact goes through six stages of friction mechanism in the running-in period before steady state period reached. Initially, friction coefficient depends on material, surface property and environmental condition. Friction force is a result of ploughing of surface by asperities, where adhesion does not play any role due to contamination present on the surface. In second stage due to polishing wear process at stage 1 surface contamination removed from surface, it results in increase friction coefficient due to increased adhesion. Third stage, wear particles entrapped between the surfaces, if the hardness of these particles is equal to the surface material they will penetrate into both surface preventing the slippage and maximize ploughing friction. At forth stage adhesion, particle entrapped between surfaces remains constant and asperity deformation continues to contribute. At fifth stage, when a stationary hard slider is slide against a soft specimen, the asperities of hard material removed and creating a mirror like surface. Friction force is decreases due to reduction in ploughing and asperity deformation. At sixth stage, both softer and hard surfaces become a mirror finish. The friction coefficient levels off and reaches a steady-state level **[23]**.

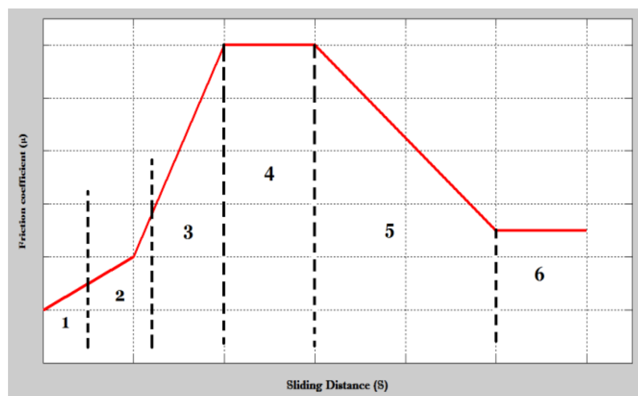

Fig. 2. Six stages of friction mechanism occurring in sliding contact at initial stage **[23]**.

Wear mechanism (**Fig. 3 a-d**) **[24]** is defined as a loss of material from the surface when two bodies are in contact. Adhesive, abrasive, fatigue, and chemical wear are the main classification of wear. At a time more than one wear mechanism can act, depends on the contact condition. Wear mode depends on contact condition, and geometry of surfaces, these are corrosive, erosive, running-in, cavitation, sliding, and rolling wear. Scuffing, pitting, scoring, spalling, seizure are the typical wear failure mode. When two materials come in contact and strongly adhere to the surface they form an asperity junction known as adhesive wear **[6, 18, 25-28]**. Abrasive wear occurs when harder material slid against softer material. It results in a plastic flow of softer material **[29-31]**. Pressure at a surface create a stress near contact zone, due to cyclic stress cracks form on the surface which increases as the Hertzian pressure increases, known as fatigue wear **[32, 33]**. Chemical process occurs between the surface interfaces which give chemical wear to the surface. Oxidation wear is the chemical wear process. A protective layer of oxides is form over the surface. When two surfaces are in contact this thin layer protect the surface and provide very low friction and wear values **[34-37]**.

Wear volume can be calculated by formula given by Archard and Holm. Wear volume is directly proportional to the normal load and distance of movement whereas it is inversely proportional to the hardness of the material.

$$Q = KWL/H$$

where, Q is the volume of wear material, K is a constant also known as coefficient of wear, L is sliding distance, and H is hardness of material. This is the most accepted wear equation till date but in some cases of tribological contacts it is invalid **[38-40]**.

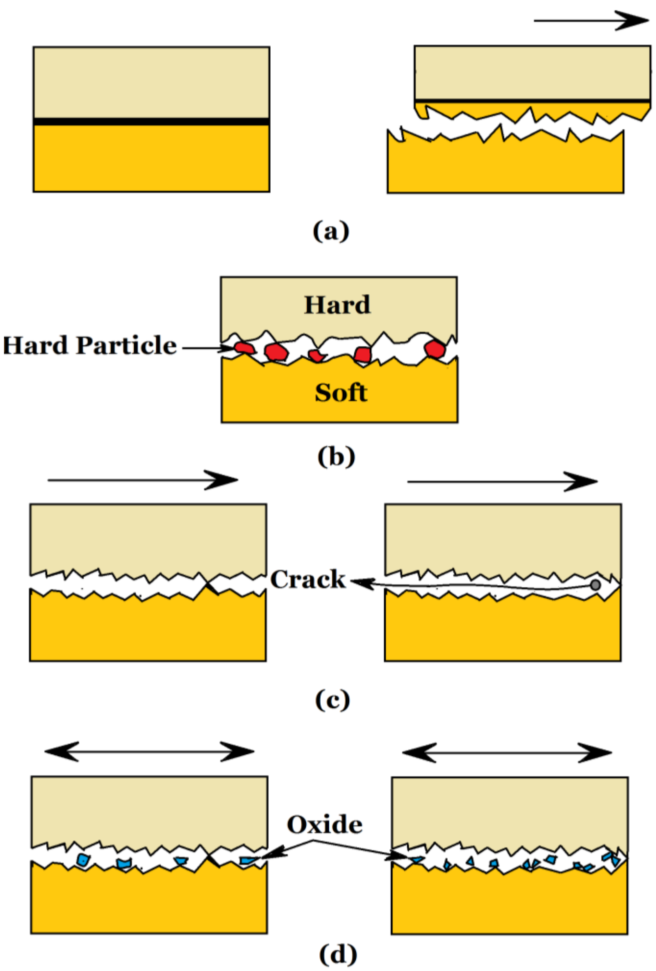

Fig. 3. Wear mechanism of (a) adhesive wear, (b) abrasive wear, (c) fatigue wear, and (d) chemical wear **[24].**

Lubrication is an art to reduce friction and wear between two contacting bodies by introducing a lubricant. It prevents contact between two surfaces, and shearing action which is responsible for resistance to motion and stress within the material. The lubrication mechanism (**Fig. 4**) divided into two main group i.e. fluid pressure lubrication, and surface film lubrication **[24]**. In Fluid pressure lubrication material surfaces are kept apart from each other by creating fluid pressure inside the lubricant and it governs by rheology, fluid dynamics. In surface film lubrication a group of lubrication mechanism involve where surfaces are kept partially apart from each other by means of protecting thin-film attached to the surface. This protecting film mainly generated by physical or chemical bonding within the surfaces, where lubricant chemistry plays an important role **[6, 24]**. Reynolds **[41]** and Tower **[42]** derived mathematical expression for the process of film formation between moving surfaces has been fundamental to all lubrication theory till date. Equation derived for various configurations of surface and gives better understanding towards elastohydrodynamic contact which helps in evaluating the optical study and infrared temperature measurements of EHL. The elastohydrodynamic of elliptical contacts have being applied to engineering components such as ball and roller bearings lubrication **[43, 44]**. Hydrodynamic pressure created within the liquid due to the relative motion of surface in contact this pressure is high enough to separate the surfaces from contact. In boundary lubrication very thin lubricant film adsorb on the surface and this lubricant film has lower shear strength then the welded asperity junction, also known as extreme pressure Lubrication **[24]**. At this regime high load and low-speed is permissible. Physical adsorption and chemical adsorption takes place to form a protective layer on the material surface which gives substantial low friction and wear rate.

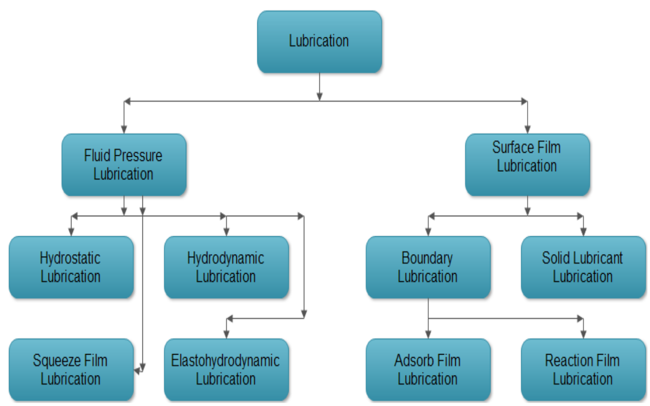

Fig. 4. Schematic of lubrication mechanism involve in tribology **[24]**.

Contact mechanics

Contact mechanics is one of the fundamental concepts used in engineering sciences. At contact points stress concentration affects processes which involve during friction interactions. Contact mechanics investigates the stress-strain properties near contact zone. Substantial increment in the temperature rise alters the surface properties due to high pressure and velocity at the contact zone. Chemical reaction takes place between the contact zones and results formation of secondary compound and structure **[45]**. Contact mechanics first evaluated by Hertz (1882) **[6, 46-48]** analyzed the stresses in the contact of two elastic solids and it based on some assumptions.

- The contacting bodies are elastic, homogeneous, and isotropic.

- The strains are small. No tangential forces acting between the solids due to load acting normal to the contact tangent plane.
- The surfaces are smooth and non- conforming.
- The contacting surfaces are at rest and in equilibrium.
- The contact is frictionless, surface roughness effect negligible.

Due to high stress and contact near the surface, crack propagates and grows in the direction of high stresses that leads to deformation and nature of this deformation can be elastic or plastic. Due to the surface treatment, surfaces have different kinds of inhomogeneity. These inhomogineities influence the stress distribution near contact interaction. Geometric inhomogeneity influences the contact characteristics such as pressure distribution, real area of contact, and stresses develop inside the surface layer. Mechanical Inhomogeneity arises due to surface treatment, where small thickness of surface layer can influence the friction and wear properties **[45]**. If two different elastic bodies are in contact some tangential displacement occurs due to the transverse expansion of the bodies. If the surface stress distribution act over a finite area than the deformation of the surface will be same at all direction. Generally, real surfaces contacts occur between asperities and the real area of contact which is normally determine by the plastic deformation of their asperities. Tribological contact process involve relative movement of surfaces which depends on some input parameters like geometry of surface from macro to micro scale, chemical composition of materials i.e. materials property and energy parameters like temperature, viscosity and load etc (**Fig. 5**) During contact material transfer, mechanical and tribological changes take place those evaluated by output result **[24, 49]**.

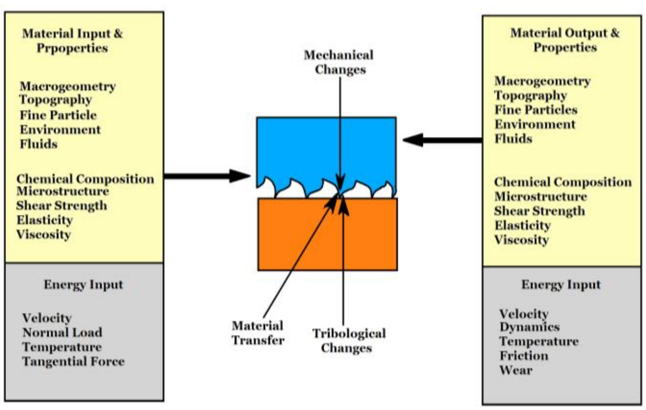

Fig. 5. Mechanism and process of material transfer between two surfaces **[24].**

Hertz in 1882, proposed a first model for contact mechanics that only considered a pure elastic contact and excluded the surface roughness effects. Hertz proposed contact model can only be used to describe each individual asperity contact. Maximum shear stresses lies inside the surface **[50, 51]**. In theory of elastic deformation surface interaction such as Van der Waals or contact adhesive interactions neglected. In Rolling contact mechanics sliding and sticking occurs in the contact zones. Reynolds proposed theory of rolling resistance due to micro slip **[52]**. Surface finish affects the friction property as slip occurs. When two surfaces loaded over another a contact zone created which depends on the curvature of the surface. At no load, contact may refer as point contact and if two surfaces have the same curvature than contact can refer as line contact **[53]**. Under high load and pressure asperities comes in contact, where the ratio of actual contact surface area to nominal is less **[54]**. The contact (**Fig. 6**) is considered to be adhesive in JKR theory (Johnson, Kendall, and Roberts) and considered as improved version of Hertzian Elastic theory. It correlates the contact area to the elastic material property and interfacial strength. Due to the adhesive contact in nature, it could form during the unloading cycle also. Van der Waals interactions outside the elastic contact regime considered in DMT theory, which gives rise in load additionally. It also includes adhesive model. According to Bradley's model effect of interaction forces neglected in elastic deformation, whereas in Van der Waals model with rigid sphere **[55, 56]**.

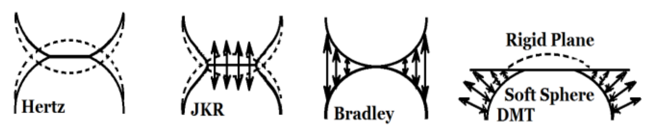

Fig. 6. Hertz, JKR, Bradley, and DMT Model **[56].**

Surface stresses in contact

Surface stresses and deformation in a coated surface were studied by Holmberg and Matthews **[24, 49]**. When two contacting bodies are press tighter by the application of force internal stresses generated. High compressive stresses effect in hard and smooth diamond coatings has been studied and found that in diamond coating internal stresses influence the crack propagation direction. High stress coatings obtain a smoother surface compared to the stress free coating and wear rate only about 5-20% of the stress free coatings **[57, 58]**. Von Mises stress distribution was analyzed in a hard coating and in elastic sliding. An elliptical distribution of pressure assumed for the Von Mises stress for wide variety of coating thickness. Diao and Kato found local yield maps which showed that coating on substrate side is the most common case under contact **[59]**. Stresses estimation under the friction load of coating and within the surface studied using Finite Element Method (FEM) **[60, 61]**. Numerical solution for different stress distribution obtained by Ramalingam and Zheng and encounters a problem as the surface coated with hard coating materials having hardness more or less than the coating material. Their result concluded that how could film thickness and coating condition adjust to withstand the stresses as the tensile strength separate the coating from the surface **[62]**. Sainsot et al. have been evaluated the roughness parameter at coating interface which plays an important role in contact stresses. They concluded that if the coating thickness less than 15µm applied on softer substrate, the Von Mises stresses located at their interface both in the coating and substrate **[63]**.

Thin film and characterizations

Film deposition process

Physical Vapour Deposition (PVD), Chemical Vapour Deposition (CVD), Thermal Spray (TS) processes are widely used in industries for coating application **[64]**. PVD coatings were developed by Faraday in 1852 **[65]**. It includes three techniques: sputtering, ion plating, and evaporation. PVD process used to apply coatings by condensation of vapours in the vacuum. Perfect adhesion takes place between the atoms of coating material and the atoms of the substrate. PVD technology is extremely versatile and it ranges from metals, ceramic to paper. In order to improve wear resistance, TiN coating deposited onto high-speed cutting tools nowadays CrN gaining importance due to its corrosion and wear resistance property **[66-68]**. PVD coated blades in gas turbine industry achieve higher life cycle.

CVD coating introduced in early sixties, it has grown very rapidly in the last thirty year. CVD process involved in fabrication of electronics devices such as semiconductor, optics and also it used in cutting tools, metallurgical industry. CVD process involves deposition of a solid material on a heated surface in vapour phase due to chemical reaction. Thermodynamics plays a vital role in CVD, Kinetics gives transport phenomena and driving force gives direction to the reaction **[69]**. Inclusion of Gas plasma enhances the process, gives wide control over the residual stresses within the coating and provides thick coating at a higher deposition rate **[64]**.

Thermal spraying coating involves heated material onto the material surface. Wire Flame and Twin-Wire Arc are the most common and cost-effective thermal spray technique producing lower bond strength and with high porosity. Metal, ceramics, alloy, plastic and composites are the common coating materials. Nowadays, use of high velocity oxy flame (HVOF) and twin wire arc (HVOF-Arc) increases continuously. It consists of compressed air and propane. HVOF coatings give less porosity that enables it to resist wear, oxidation, and corrosion. Plasma spray provides good thermal barrier for coating. **[64, 70-74]**.

Table 1. Analytical techniques used in thin-film characterization.

Measurement technique	Energy range	Primary beam and secondary signal	Application
SEM	0.3 - 30KeV	Electron - Electron	Surface morphology
TEM	100 - 400KeV	Electron – Electron	High resolution structure
AES	500eV - 10KeV	Electron – Electron	Surface layer composition
LEED	20 - 200eV	Electron – Electron	Surface structure
EMP (EDX)	1 - 30KeV	Electron – X-Ray	Surface region composition
STEM	100 - 400KeV	Electron – Electron	X-ray analysis, imaging
EELS	100 - 400KeV	Electron – Electron	Local small area composition
SNMS	1 - 15eV	Ion - Atom	Trace composition vs depth
ISS	0.5 – 2KeV	Ion - Ion	Surface composition
PIXE	1KeV	Ion - X-Ray	Trace composition
SIMS	1 – 15KeV	Ion - Ion	Trace composition vs depth
SIM	5 – 20KeV	Photon - Electron	Surface characterization
XPS	> 1KeV	Photon - Electron	Surface composition
XRD	> 1KeV	Photon – X-Ray	Crystal structure
RBS	> 1MeV	Photon - Ion	Composition vs depth
XRF	> 1KeV	Photon - X-Ray	Composition (1μm)

***Abbreviation:** *SEM- Scanning Electron Microscopy, TEM- Transmission Electron Microscopy, AES- Auger Electron Spectroscopy, LEED- Low-Energy Electron Diffraction, EMP- Electron Microprobe, STEM- Scanning TEM, EELS- Electron Energy Loss Spectroscopy, SNMS- Secondary Neutral Mass Spectroscopy, ISS- Ion-Scattering Spectroscopy, PIXE- Particle-Induced X-Ray Emission, SIMS- Secondary Ion-Mass Spectroscopy, SIM- Scanning Ion Microscopy, XPS- X-Ray Photo Electron Spectroscopy, XRD- X-Ray Diffraction, RBS- Rutherford Backscattering, XRF- X-Ray Fluorescence* [**86**].

Characterization of thin films

Thin film deposition technology has advanced during the last thirty years, and driven due to need for new product and devices in the industry. It is a well establish technology and versatile means of improving component performance. The coating substrate possesses enough toughness to resist stresses and avoid equipment failure. Tribological coating adds physical properties such as hardness, lubricity, and resistance to corrosion, to the lower valued substrate to increase the overall quality of the component **[75]**. Wide variety of coating is available for the tribological application. Diamond, diamond like carbon, nitride, and related materials offers new coating strategy which gives significant impact on modern-day life. These days multilayer coating getting attention in tribological application, it reduces friction and wear to considerable limit. This is a hard thick coating consisting of two materials in order to get considerable hardness and to combine the properties of constituent materials **[24, 76-84]**. Optical instruments used to evaluate surface characteristic but nowadays due to technology enhancement surface intrinsic property plays a vital role to explore this area.

Thermal characterization of coating includes differential scanning calorimetry (DSC), differential thermal analysis (DTA), thermomechanical analysis (TMA), thermogravimetric analysis (TGA) and dynamic mechanical analysis (DMA). DSC operates at -180 to +725 ^{o}C and evaluates heat flow and temperature with chemical reaction with respect to reference material. Operating condition for DTA is -180 to +1600 ^{o}C and it replaced by DSC due to accuracy. TMA measures dimension changes within the material as a function of time, temperature and operates at -160 to +1200 °C. TGA measures change in mass as a function of time, temperature. It neither reveals about absorption nor transmission. TGA operates at ambient to 1200 °C. DMA gives property of materials under stresses, it detects sample at -150 to +500 °C.

A new demand has been arisen in the field of film characterization. Coating technology is interdisciplinary in nature and varies from material to material. Material internal behaviour is an important parameter for surface engineering. To evaluate these internal and outer properties of material and thin-film analytical instruments used to characterise the surface phenomena were listed in **Table 1** **[85, 86]**. Analytical instruments to analyse surface coating are XRD, SEM, TEM, AES, XPS, SIMS, and RBS. AES has been used to measure the elemental composition to the depth. AES provides the X-ray microanalysis (EDX) information. SIMS measure charge particles scattered from a surface, this gives the thin surface film composition. XRD provides residual stress, grain size, phase composition and texture **[87-91]**.

Mechanical property

Hardness of the coating and stresses developed in the film affects the mechanical properties of the thin films. Mechanical property of a coating depends on the type and magnitude of stresses. Coating hardness dominates the wear property of the material. Young's modulus becomes an important calculation part of stress. Less young's modulus may result in low strength demand on substrate **[75]**. Internal stresses present in thin-film directly affect adhesion, and generation of crystalline defects. Adhesion (**Fig. 7**) of the coating evaluating by the scratch tester **[8, 9]** in which a indenter was moved across the coated surface with increasing load and coating delamination was found. Mechanical properties of coating surfaces are evaluate by tensile testing, bulge testing, indentation testing, and deflection of micro beams **[92]**. This has enabled the study of a mechanical behaviour of thin-film and surface coating with accuracy.

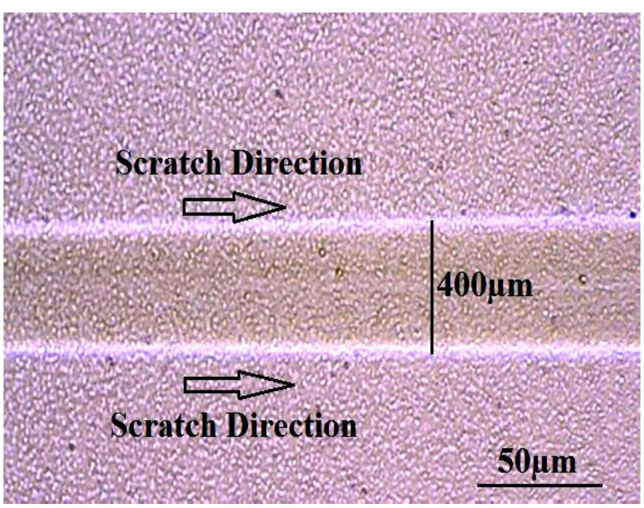

Fig. 7. Adhesion test result of coated steel **[8, 9].**

Mechanism that affects the nanomechanical behaviour of multilayered systems is image force effect, Orowan strengthening, Hall-Petch behaviour, composition modulation, and coherency and thermal stress **[5]**. Evaluation of Nanomechanical properties of thin films can split into two methods, first point probes and second complimentary methods. Complementary methods can be used separately or with point probes and it includes Raman spectroscopy to high energy diffraction study **[5]**. Indentation **[92]** technique is now most popular due to its simplicity, easiness and widely used to estimate mechanical properties of small volume i.e. thin films. These days depth sensing device i.e. nanoindentation, used to study the mechanical property of thin films, see **Fig. 8**.

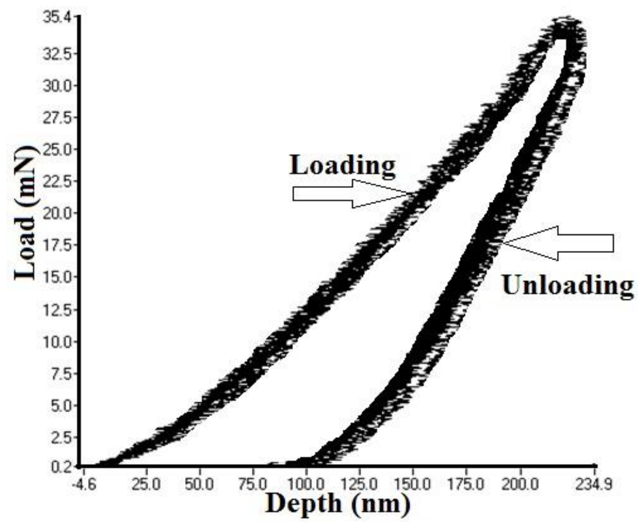

Fig. 8. Schematic of nanoindentation plot between depth of penetration and applied load **[8]**.

Conventional indentation instruments can give only hardness when known force is applying, it may measure by using projected area of the impression. To measure the internal hardness of the film indentation depth must below ten times than a film thickness otherwise the composite hardness influenced by the substrate will measure. In nano-indentation, penetrations of the indenter as a function of applied load were measure. Mechanical property of thin-film becomes very sensitive to the surface roughness, elastic modulus and hardness of material estimated by displacement vs resulting load curve **[92, 93]**. To measure the size of the indents, nanoindentation method developed to record the displacement, time, stiffness, and load continuously throughout the indentation process developed by Soviet Union and applied in the early 1980s **[5, 94-100]**. An external load applied to the indenter tip during nanoindentation test shown in **Fig. 9 [5]**. This intender made to push into the sample as the load applied and creates a nano scale impression on the sample. Conventional indentation test perform by pressing a tip to the sample of known geometry and fixed load, at last created indentation area will measure. Rockwell, Vickers, and the Knoop test used to measure the hardness. Rockwell hardness test perform by pushing a ball with minor load, a major load, again minor load into the sample and calculating the depth as L_1, L_2, L_3. In Vickers hardness testing four-sided pyramid pushed into the sample with a known load. Indentation area measured optically and the hardness calculated as the load divided by area. Knoop indentation uses the same principal of hardness as the Vickers test, load divided by area, with one long diagonal and one short diagonal indenter geometry.

Interface between the film and substrate affected by many variables and it affects the elastic, plastic behaviour of film. This consideration must take into account when prepare a model to test the performances of thin-film and interface. Coated system can divided in many categories neglecting the effect of interface and depends on the elastic modulus (E) and yield strength (Y) **[101-103]**.

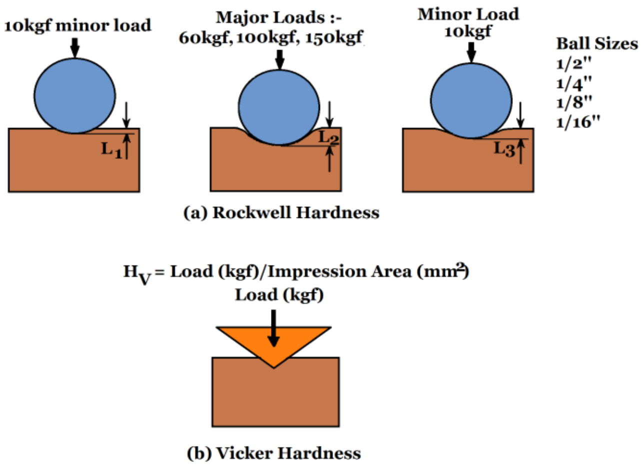

Fig. 9. Schematic Diagram of Rockwell, Vickers, and Knoop Hardness Indentation testing methods **[5].**

Conclusion and future directions

Tribology research has been now emerging area for technologist in recent times. Tribological studies past the level from macro study to nano level. Various emerging technologies like Atomic force microscopy (AFM), and Surface force apparatus influence friction and wear behaviour. Wear debris attached to the counterface may form a transfer layer and affects the tribological properties. Nanomechanical behaviour of thin-film and surfaces has been largely studying during past years. Electronics industry also adapted the thin-film application in MEMS **[104]** devices. A nanomechanical property such as viscoelastic, temperature, physics and chemistry of surfaces is likely to grow in the near future for the biological sector. Thin film application includes microelectronics, optoelectronics industries, telecommunicating devices, wear resistance coating, sensors, decorative coating, biotechnology, and energy conservation.

Friction and wear study at atomic level needs more attention, over the last twenty year development of friction force microscopy (FFM) and computer simulation helps to investigate friction of single asperity contact and opens the door for Nanotribology. Nanotribology includes nanometer scale friction behaviour study of materials, atomic forces distinguishes tribology and nanotribology that responsible for measuring the systems final behaviour. At the interfaces contact occurs at various asperities, study of these contacts with the help of microscopy probe (Atomic Force Microscopy, and Scanning Tunneling Microscope) and computational techniques that enables an investigation of interfacial problems with high-resolution. These advances have led to the development in the field of Nanotribology or atomic-scale tribology **[105-110]**. Nanotribology includes theoretical as well as experimental studies ranging from atomic scale to microscales that occur during friction, wear, lubrication and adhesion at sliding contacts. In macrotribology, tests conducted with a large mass and heavy loaded condition where properties of mating components dominate the tribological behaviour. In this condition wear is more. In nanotribology tests conducted with small mass and light load condition, where wear is negligible and tribological performance dominated by surface properties. This field requires the understanding of interfacial phenomena **[5]** that helps to understand thin-film behaviour at nanoscale.

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Reference

1. Jost, P.; Lubrication (Tribology) – A Report on the Present Position and Industry's Needs. Dept. of Education and Science (H.M. Stationary Office), **1966**.
2. Dowson, D.; History of Tribology. Inst. Mech. Engineers, 2nd edition, **1998**.
3. Davidson, C.S.C.; Bearings since the Stone Age. Eng., 183:2–5, **1957**.
4. Layard, A.G.; Discoveries in the Ruins of Nineveh and Babylon, volume I, II. Murray, **1853**.
5. Bhusan, B.; Nanotribology and Nanomechanics, springer, ISBN-13 978-3-540-24267-3 Germany, **2005**.
6. Stachowiak, G.W.; Engineering Tribology, 3rd ed., U.S.A., **2005**.
7. Kalin, M.; Simic R.; *Appl. Surf. Sci.* **2013**, *271*, 317.
   DOI: 10.1016/j.apsusc.2013.01.192.
8. Upadhyay, R.K.; Kumaraswamidhas, L.A.; *Surf. Engg.* **2014**, *30 (7)*, 475.
   DOI: 10.1179/1743294414Y.0000000260.
9. Upadhyay, R.K.; Kumaraswamidhas, L.A.; *Mate. at High Temp.* **2014**, *31 (2)*, 102.
   DOI: 10.1179/1878641314Y.0000000003.
10. Amann, T.; Dold, C.; Kailer, A.; *Trib. Int.* **2013**, *65*, 3.
    DOI: 10.1016/j.triboint.2013.03.021.
11. Upadhyay, R.K.; Kumaraswamidhas, L.A.; *Chem. Phys. Lett.* **2014,** 608, 167.
    DOI: 10.1016/j.cplett.2014.05.090.
12. Wang, Y.M.; Guo, J.W.; Zhuang, J.P.; Jing, Y.B.; Shao, Z.K.; Jin, M.S.; Zhang, J.; Wei, D.Q.; Zhou, Y.; *Appl. Surf. Sci.* **2014**, *299*, 58.
    DOI: 10.1016/j.apsusc.2014.01.185.
13. Agarwal, K.; Shivpuri, R.; Vincent, J.; Rolinski, E.; Sharp, G.; *J. Mate. Process. tech.* **2013**, *213*, 864.
    DOI: 10.1016/j.jmatprotec.2013.01.002.
14. Strauss, H.w.; Chromik,R.R.; Hassani, S.; Klemberg-Sapiehab, J.E.; *Wear*, **2011**, *272*, 133.
    DOI: 10.1016/j.wear.2011.08.001.
15. Rmaile, A.; Carugo, D.; Capretto, L.; Zhang, X.; Wharton, J.A.; Thurner, P.J.; Aspiras, M.; Ward, M.; Stoodley, P.; *Wear*, **2013**, *306*, 276.
    DOI: 10.1016/j.wear.2013.02.010.
16. Jiao, D.; Zheng, S.; Wang, Y.; Guan, R.; Cao, B.; *Appl. Surf. Sci.* **2011**, *257*, 5720.
    DOI: 10.1016/j.apsusc.2011.01.084.
17. Jones, M.H.; Scott, D.; Industrial tribology, The Netherlands, 1st ed., Tribology Series 8, **1983**.
18. Buckley, D.H.; *Wear*, **1978**, 46 (1), 19. (DOI: 10.1016/0043-1648(78)90109-6).

19. Buckley, D.H.; Surface Effects in Adhesion, Friction and Wear, **1981**, Elsevier, Tribology Series 5, Amsterdam.
20. Reidenbach, F.; ASM Handbook of Surface Engineering, vol. 5, **1994**.
21. Amontons, G.; De la resistance causee dans les machines. Mem. Acad. R. A, *257–282*, **1699**.
22. Coulomb, C.A.; Theorie des machines simples, en ayant regard an frottement de leurs parties et a la roideur des cordages. Mem. Math. Phys. X, Paris,:*161– 342*, **1785**.
23. Suh, N.P.; Sin, H.C.; *Wear*. **1981**, *69 (1)*, 91. **DOI:** 10.1016/0043-1648(81)90315-X.
24. Holmberg, K.; and Matthews, A.; Coatings Tribology—Properties, Techniques and Applications in Surface Engineering (Elsevier Tribology Series, Vol. 28). Elsevier Science B.V., 2nd Ed., Netherlands, **1994**.
25. Buckley, D.; Surface effects in adhesion, friction, wear, and lubrication. Elsevier, Amsterdam, **1981**, pp.631.
26. Buckley, D.; Properties of surfaces. In: CRC Handbook of Lubrication –Theory and Practice of Tribology, **1993**.
27. Bowden, F.P.; Tabor, D.; Friction and Lubrication of Solids. Part I. Oxford, Oxford UP, Oxford, UK, **1950**, pp.321.
28. Bowden, F.P.; Tabor, D.; The friction and Lubrication of Solids. Part II. Oxford, Oxford UP, UK, **1964**,515.
29. Hokkirigawa, K.; Kato, K.; *Trib. Int.* **1988**, *21 (1)*, 51. **DOI:** 10.1016/0301-679X(88)90128-4.
30. Hokkirigawa, K.; Kato, K.; Li, Z.Z.; *Wear*, **1988**, *123 (2)*, 241. **DOI:** 10.1016/0043-1648(88)90102-0.
31. Hutchings, I.M.; Tribology: Friction and Wear of Engineering Materials. Edward Arnold, London, **1992**, pp.273.
32. Schouten, M.J.W.; Einfluss elastohydrodynamischer schmierung auf reibung, verschleiss und lebendsdauer von Getrieben/The influence of elastohydrodynamic lubrication on friction, wear and lifetime in gear transmissions/. Doctoral thesis, Eindhoven Technical University, **1973**a. pp.388.
33. Schouten, M.J.W.; Der einfluss elastohydrodynamischer schmierung und reibung, verschleiss und lebendsdauervon Getrieben/The influence of elastohydrodynamic lubrication on friction, wear and lifetime.
34. Quinn, T.F.J.; *Trib. Int.* **1983**, *16 (5)*, 257. **DOI:** 10.1016/0301-679X(83)90086-5.
35. Quinn, T.F.J.; *Tribology Int*. **1983**, *16 (6)*, 305. **DOI:** 10.1016/0301-679X(83)90039-7.
36. Sullivan, J.L.; The role of oxides in the protection of tribological surfaces – Part 1. Inst. Mech. Eng., C143/87, **1987**, 283.
37. Sullivan, J.L.; The role of oxides in the protection of tribological surfaces – Part 2. Inst. Mech. Eng., C144/87, **1987**, 293.
38. Holm, R.; Electric Contacts. Hugo Gebers Forlag, Stockholm, **1946.**
39. Archard, J.F.; *J. Appl. Phys*. **1953**, *24 (8)*, 981. **DOI:** http://dx.doi.org/10.1063/1.1721448.
40. Archard, J.F.; Wear theory and mechanisms. In: Wear Control Handbook. Peterson, M.B., Winer, W. (eds), ASME, New York, **1980**, 35–80.
41. Reynolds, O.; *Phil. Trans. Roy. Soc*. **1886**, *177*, 157. **DOI:**10.1098/rstl.1886.0005.
42. Cameron, A.; Proc. Inst. Mech. Engrs., **1979**, *193*, Preprint No.25, London.
43. Johnson, K.L; Tevaarwerk, J.L.; *Proc. Roy. Soc. A*., **1977**, *356*, 215. **DOI:** 10.1098/rspa.1977.0129.
44. Hancock, B.T.; Dowson, D.; Ball Bearing Lubrication - The Elastohydrodynamics of Elliptical Contacts, **1981**, Wiley & Sons, N.Y.
45. Goryacheva, I.G.; Contact mechanics in tribology, Vol. 61, The Netherlands, **1998**.
46. Hertz, H.; Reine, J.; Mathematik, A.; Uber die Beruhrung Fester Elastischer Korper, (On the Contact of Elastic Solids), Vol. *92*, **1881**, pp. 156-171.
47. Hamrock, B.J.; Dowson, D.; Ball Bearing Lubrication, the Elastohydrodynamics of Elliptical Contacts, John Willey & Sons, **1981**.
48. Hertz, H.; Miscellaneous Papers by Hertz, H., Jones & Schott (eds), Macmillan, London, **1986**.
49. Holmberg, K.; Matthews, A.; Ronkainen, H. *Trib. Int*. **1998**, *31 (1-3)*, 107. **DOI:** 10.1016/S0301-679X(98)00013-9.
50. Greenwood, J.A.; Williamson, J.B.P.; *Proc. Roy. Soc. London A*. **1966**, *295*, 300. **DOI:** 10.1098/rspa.1966.0242).
51. Pugliese, G.; Tavares, S.M.O.; Ciulli, E.; Ferreira, L.A.; *Wear*, **2008**, *264 (11-12)*, 1116. **DOI:** 10.1016/j.wear.2007.08.027.
52. Reynolds, O.; on rolling friction. *Phil. Trans. Royal Soc.* **1876**, *166*, 315. **DOI:** 10.1098/rstl.1876.0012.
53. Stolarsky, T.A.; Tobe, S.; Rolling Contacts, UK, **2000**.
54. Shpenkov, G. P.; Friction Surface Phenomena, Netherlands, **1995**.
55. courses.washington.edu/Ch_2_Contact%20Mechanics.pdf DOA: **22.06.2014**.
56. Johnson, K.L.; Contact Mechanics, **1985**, Cambridge University Press, Cambridge.
57. Gunnars, J.; Alahelisten, A.; Surf. Coat. Tech. 1996, *80 (3)*, 303. **DOI:** 10.1016/0257-8972(95)02436-0.
58. Gåhlin, R.; Alahelisten, A.; Jacobson, S.; *Wear*, **1996**, *196 (1-2)*, 226. **DOI:** 10.1016/0043-1648(95)06907-0.
59. Diao, D.; Kato, K.*; Thin Solid Films*, **1994**, *245 (1-2)*, 115. **DOI:** 10.1016/0040-6090(94)90886-9.
60. Diao, D. F.; Kato, K.; Hayashi, K. *Trib. Int.* **1994**, *27(4)*, 267. **DOI:** 10.1016/0301-679X(94)90006-X.
61. Wong, S. K.; Kapoor, A.*; Trib. Int*. **1996**, *29(8)*, 695. **DOI:** 10.1016/0301-679X(96)00015-1.
62. Ramalingam, S.; Zheng, L.; *Trib. Int*. **1995**, *28(3)*, 145. **DOI:** 10.1016/0301-679X(95)98963-E.
63. Sainsot, P.; Leroy, J. M.; Villechaise, B.; Effect of surface coatings in a rough normally loaded contact. In Mechanics of Coatings (Elsevier Tribology Series, Vol. *17*), ed. Dowson, D., et al. Elsevier, Amsterdam, **1990**, pp. 151–156.
64. Stewart, S.; Ahmed, R.; *Wear* **2002**, *253* (11-12), 1132. **DOI:** 10.1016/S0043-1648(02)00234-X.
65. Faraday, M.; *Philos. Trans. R. Soc.* **1857**, *147*, 145. **DOI:** 10.1098/rstl.1857.0011.
66. Chiba Y.; Omura T.; Ichimura H.; *J. Mater. Res.* **1993**; *8 (5)*, 1109. **DOI:** http://dx.doi.org/10.1557/JMR.1993.1109.
67. Bin T.; Xiaodong Z.; Naisai H.; Jiawen H.; *Surf. Coat. Tech.* **2000**, *131(1-3)*, 391. **DOI:** 10.1016/S0257-8972(00)00769-6.
68. Sue J.A.; Chang T.P.; *Surf. Coat. Technol*. **1995,** *76-77*, 61. **DOI:** 10.1016/0257-8972(95)02506-5.
69. Pierson, H.O.; Handbook of chemical vapour Deposition (CVD), 2nd ed., U.S.A, **1999**.
70. Gorlach, I.A.; *Thin Solid Films* **2009**, 517 (17), 5270. (DOI: 10.1016/j.tsf.2009.03.174).
71. Xu, B.; Zhu, Z.; Yan, Y.L.; Ma, S.; Chen, Y.; Proceedings of the International Thermal Spray Conference, Basel, Switzerland**, 2005**.
72. Kosikowski, D.; Batalov, M.; Mohanty, P.S.; Proceedings of the International Thermal Spray Conference, Basel, Switzerland, **2005**.
73. Verstak, A.; Baranovski, V.; Proceedings of the International Thermal Spray Conference, Osaka, Japan**, 2004**.
74. Wang, R.; Lin, X.; Tianjian, Z.; Xiaoou, H.; Proceedings of the International Thermal Spray Conference, Osaka, Japan, **2004**.
75. Meneve, J.; Vercammen K.; Dekempeneer, E.; Smeets, *J.; Surf. Coat. Tech*. **1997**, *94-95*, 476. **DOI:** 10.1016/S0257-8972(97)00430-1.
76. ASM Handbook, friction Lubrication and Wear Technology, Vol.18, 1st ed., ASM International, Ohio, **1992**, p. 827.
77. Dan, J.P.; Boving, H.J.; Hintermann, H.E.; J. de Physique **1993**, *IV*, 3(C7), 933.
78. Seal, J.E.; Field, J.E.; (ed.), the Properties of Natural and Synthetic Diamond, Academic Press, London, **1992**. p.607.
79. Watanabe, S.; Miyake, S.; Murakawa, M.; Tribological Pefformnnce of Cubic BN Film, accepted for publication in Diamond films Technology - special issue on c-BN films and related materials, 7, **(1997**).
80. Ehrhardt, H.; *Surf. Coat. Tech*. **1995**, *74-75*, 29. **DOI:** 10.1016/0257-8972(95)08212-3.
81. Grill, A.; *Wear*, **1993**, *168 (1-2)*, 143. **DOI:** 10.1016/0043-1648(93)90210-D.
82. Meneve, J.; Dekempeneer, E.; Smeets, J.; *Diamond Films Technology* **1994**, *4*, 23.
83. Sproul, W.D.; *Surf. Coat. Tech*. **1996**, *86-87*, 170. **DOI:** 10.1016/S0257-8972(96)02977-5.
84. Nordin, M.; Larsson, M.; Hogmark, S.; *Wear*, **1999**, *232 (2)*, 221. **DOI:** 10.1016/S0043-1648(99)00149-0).
85. Bindell, J.B.; VLSI Technology, 2nd ed., S. M. Sze. McGraw-Hill, New York**, 1988**.

86. Ohring, M.; Materials Science of Thin Films, Deposition and Structure, 2nd ed.
87. Tracton, A. A.; Coatings Technology Handbook, 3rd ed., CRC press, Boca Raton FL, **2006**.
88. Bishop, H.E.; Auger electron spectroscopy. In: Methods of Surface Analysis. Walls, J.M. (ed.), Cambridge University Press, **1989**, 87–126, pp.36.
89. Chalker, P.R.; Characterisation of coatings and interfaces. Advanced Surface Coatings – A Handbook of Surface Engineering. Rickerby, D.S.; Matthews, A.; (eds), Blackie, London, **1991**, 278–314.
90. Christie, A.B.; X-ray protection spectroscopy. In: Methods of Surface Analysis. Walls, J.M. (ed.), Cambridge University Press, **1989**, 127–168.
91. Quaeyhaegens, C.; Van, S.M.; Stals, L.M.; Bodart, F.; Terwagne, G.; Vlaeminck, R.; *Surf. Coat. Tech*. **1992**, *54-55*, 279. **DOI:** 10.1016/S0257-8972(09)90063-9.
92. Ahn, J.H.; Kwon, D.; *Materials Science and Engineering A*. **2000**, *285 (1-2)*, 172. **DOI:** 10.1016/S0921-5093(00)00696-1.
93. Bobji, M.S.; Biswas, S.K.; *J. Mater. Res*., **1998**, *13 (11)*, 3227-3233.
94. Bulychev, S.I.; Alekhin, V.P.; Shorshorov, M.Kh.; Ternovskii, A.P.; Shnyrev, G.D.; Zavod Lab., 41:1137, 1975.
95. Ternovskii, A.P.; Alekhin, V.P.; Shorshorov, M.Kh.; Khrushchov, M.M.; Skvortsov, V.N. Zavod Lab., 39:1242, **1973**.
96. Shorshorov, M.Kh.; Bulychev, S.I.; Alekhin, V.P. Sov. Phys. Doklady, 26:769, **1982**.
97. Bulychev, S.I.; Alekhin, V.P.; Shorshorov, M.Kh.; Ternovskii, A.P.; Prob. Preachinging., 9:79, **1976**.
98. Bulychev, S.I.; Alekhin, V.P.; Zavod Lab., 53:76, **1987**.
99. Newey, D.; Wilkens, M.A.; Pollock, H.M.; *J. Phys. E. Sci. Instrum*. **1982**, *15*, 119.
100. Pethica, J.B.; Microhardness tests with penetration depths less than ion implanted layer thickness, Pergamon, **1982**, pp 147.
101. Whitehead, A. J., Page, T.F. NATO ASI Ser. E. **1993**, 233, 481.
102. Whitehead, A.J., Page, T.F., *Thin Solid Films*, **1992**, 220 (1-2), 277. (DOI: 10.1016/0040-6090(92)90585-Y).
103. Fabes, B.D.; Oliver, W.C.; McKee, R.A.; Walker, F.J. J.; Mater. Res., **1992**, 7, 3056.
104. Rymuza Z.; *Microsyst. Tech*. **1999**, *5 (4)*, 173. **DOI:** 10.1007/s005420050160.
105. Bhushan, B.; Introduction to Tribology. Wiley, **2002**.
106. Bhushan, B.; Springer Handbook of Nanotechnology. Springer, **2004**.
107. Bhushan, B.; Israelachvili, J.N.; Landman, U. *Nature*, **1995**, *374*, 607. **DOI:** 10.1038/374607a0).
108. Bhushan, B.; Micro/Nanotribology and its Applications. NATO ASI Series E: Applied Sciences 330. Kluwer Academic, **1997**.
109. Bhushan, B.; Handbook of Micro/Nanotribology. CRC, 2nd ed, **1999**.
110. Bhushan, B.; Fundamentals of Tribology and Bridging the Gap Between the Macroand Micro/Nanoscales, volume 10 of NATO Science Series II: Mathematics, Physics, and Chemistry. Kluwer Academic, **2001**.

