Prof. N.K.Myshkin

Notes to Lecture for KSLE

TRIBOLOGY:STATE OF THE ART AND ADVANCES IN CIS

Abstract

General state of research in fundamentals and applied areas of tribology is analysed with taking account of changes in structure of funding and other aspects of transfer from centralized state economy to market one under simultaneous effect of USSR disintegration to independent states. Belarus Tribology Society as a coordinating body is presented. Activities of the major centers of research in friction, wear and lubrication are shown.

Recent advances in development of analytical and calculation methods, surface characterization, wear testing and standardization, condition monitoring and tribomaterials are considered.

Introduction

Tribological research in the former USSR has a relatively long history. It can be started from the fundamental works of Prof. Petroff in the end of the 19-th century when he has found the basic laws of hydrodynamic lubrication and reported them in the same time as O.Reynolds in UK. Names of B.Deryaguin and I.Kragelskii have become a part of tribology foundation in 30-ies and 40-ies together with F.Bowden and D.Tabor names in the West. After the Second World War elastohydrodynamics has been first established by A.Grubin in 1949 and the fatigue theory of wear has been developed by I.Kragelskii and his colleagues.

Advances in space exploration have requested numerous tribological developments in order to meet severe requirements of the extreme conditions.

Before the disintegration of USSR the whole structure of tribological research has been formed under the auspice of the USSR Academy of Sciences beeing an association of research institutes funded by government. The Council on Friction, Wear and Lubrication has been established in 1961. Its main task was to coordinate research and development in research institutes of Academy, universities and laboratories in industrial research institutes, as well as in industry. The Council has formed research programmes and applied to the government for the funding which has been provided via the State Committee on Science and Technology. National Committee on Tribology has been established by the Council in order to represent Soviet tribology community in the international scale.

Following are the major centers of tribology research in former USSR:

Moscow, - Institute for Problems in Mechanics of Russian Academy of Sciences (IPM RUS) has a laboratory of friction and wear with a staff about 15 people mostly involved in contact mechanics calculations and simulation; Mechanical Engineering Research Institute of RUS (MERI) has a large Tribology department with about 50 in staff mostly involved in friction materials, elastohydrodynamic bearings, coatings and surface treatments, friction and wear testing, design of gears, brakes and seals, ball bearings, friction in vacuum; Institute of Elementorganic Chemistry of RUS (IEC) has a laboratory involved in high-temperature friction materials and lubricants; Institute of Petroleum Chemistry of RUS (IPC) has a group involved in additives research; Railroad Research Institute has groups in friction of metals and graphite composites; Oil and Gas Academy has laboratories in metals friction, composites and ceramics;

St.Petersburg, - Institute of Machinery Problems of RUS has groups in lubricants and additives;

Kiev, - Institute of Materials Science of the Ukrainian Academy of Sciences (IMS) has laboratory involved in surface coatings; Institute of Superhard Materials of UAS has laboratory in abrasive wear; Institute of Aviation Engineers has groups in engine tribology, ceramics and lubrication.

Kharkov, - Institue of Low Temperatures of UAS has groupes in cryogenic friction, self-lubricants, wear testing.

Minsk, - Physical-Technical Institute of Belarus Academy of Sciences (PTI) is doing research in friction under metal forming conditions; Institute of Machines Reliability of BAS (IRM) has groups in boundary lubrication and ceramics; Powder Metallurgy Institute (PMI) is doing research in brake materials and wear testing;

There are also smaller tribology groupes in many polytechnical institutes around the country. Some other centers of tribology research will be mentioned below.

The staff with degrees is devided between the Academy of Sciences, polytechnical institutes and industry as approximately 30 to 60 to 10 %. The flow of papers, however was divided in inverce proportion 60 to 30 to 10 % which can be explained by teaching duties of the staff in polytechnics.

Education and professional carrier in research have been provided in the undergraduate level through the courses in the polytechnical institutes and in the postgraduate level both in these institutes and in the research institutes of the Academy of Sciences. Ph.D degree in Tribology has been given by the institutes of the Academy (Mech.Eng.Res.Inst. in Moscow, Metal-Polymer Research Inst. in Gomel, Physical-Technical Inst.in Yakutsk) and polytechnical institutes in Moscow, Tver, Tallinn, Minsk, Kiev and Odessa. Typical number of Ph.D degrees given annually was between 20 and 30 in 80-ies.

Information exchange and transfer have been realized through the conferences and seminars, as well as through journal publications and books. Two or three national conferences a year was a typical number in 80-ies. Starting from 1980 Soviet Journal of Friction and Wear has been published bimonthly, some other journals as Machine Science, Problems of Strength, Journal of Engineering Physics have published papers on friction, wear and lubrication. The Editorial Board of Friction and Wear Journal evaluated the total number of the authors published their papers in all aspects of tribology as about two thousand.

Resuming this brief introductory notes it should be mentioned that activity in tribology area in former USSR was quite impressive in scale. Nevertherless the large portion of this activity was in fundamentals with poor relation to industrial applications or it was related to defence sector of economy weakly connected with the other parts of industry. Government funding provided without competition has certain negative effect on technology transfer even the fundamentals of tribology were developed extensively.

Effect of USSR Disintegration on Tribology

The effect of political changes in USSR starting in 1991 with disintegration of former union to independent republics and following transformation of state economy to market one was multiple and rapid. First area which was effected was the coordination of research and previous national programms. After separation of the central power to different republics the whole system of funding research has been changed and money distribution has come to republican governments. It was not bad in some cases like in Belorussia, where the parliament has allocated to science even more money than central government before but in most of republics the funding has shrunked and further inflation has made the situation in academic research catastrophic.

The biggest research communities in Russia and Ukraine have suffered most severely.

The other effect was the loosening in scientific relations between republics. Even infrastructural problems like mail delays or necessity to have visa for entrance into some rebublics have arised which has produced negative influence on information transfer, conferences participation etc.

Tribology Research in Belarus Republic (Belorussia)

Belarus Republic formally named so after getting independence has a population of about 11 mln people on the area of 90 thousand sq. km. situated in the western part of former USSR near Poland. It has a relatively developed infrastructure and industry including machinery (heavy trucks, tractors and tools), electronics, petrochemistry and plastics.

Traditions of tribology research were strong in Belarus since 60-ies located im cities of Minsk and Gomel where such research institutes of Belarus Academy of Sciences as Metal-Polymer Research, Durability of Machines and Physical-Tchnical Institute are placed. After getting the independence the Belarus Tribology Society has been established which has become a member of International Tribology Council in 1993.

Metal-Polymer Research Institute (MPRI) has a total staff of more than 500 people with about 300 in research and more than 200 in design and prototype plant. There is about 60 staff members with Ph.D degree and 12 with D.Sc. degree. Funding of MPRI consists of 30 % direct government fund via the Academy of Sciences, 20 to 25 % from grants via Fund of Fundamental Research and others, and 40 to 45 % from indusrial contracts.

Tribology is one of the main subjects of research in MPRI and Tribology department includes 20 staff (8 Ph.D. and 2D.Sc.). There is also other departments as surface physics and chemistry carrying out tribology research. MPRI hosts Journal of Friction and Wear Editorial Board and is a cosponcor of the Belarus Tribology Society.

Tribology department includes four research groups involved in surface characterization, contact mechanics, electrical contacts, and wear testing. Equipment include SEM, STM, and AFM, more than ten wear test rigs and necessary computer facilities.

Advances in Tribology Research and Development

Surface Phenomena at Boundary Lubrication.

Surface phenomena have a profound part in adhesion, friction, lubrication and wear. A general systematic view on this phenomena can be presented by Fig.1. We can separate the history of surface material including previous treatment, shape parameters, environmental effects and internal defects in surface layer.

Structure of the surface layer can be schematically presented in Fig.2. It includes layer of adsorbed gases and water, oxides, amorphous Beilby layer, work-hardened layer and bulk material.

Effect of surface phenomena in a very important practical case of boundary lubrication can be considered using as an example Rebinder's effect. It's main essence is the action of surface-active compounds on mechanical properties of solid. The effect can be dual: the softening of surface layer due to reduction of surface resistance to plastic strain and also penetration of surface-active agents inside microcracks resulting in fracture of surface layer.

Because lubricants and their additives often posess surface-active properties the Rebinder effect is very important for boundary lubrication.

The schematic view of active components adsorption on the metal surface is shown in Fig.3. These groups of active radicals can protect surface against fracture in friction. Under typical conditions the increase in temperature can result in desorientation of boundary layer and seizure but the active component can have the ability to modify its structure so as to form a new protective film efficient at higher temperatures. This effect is illustrated by Fig.4.

One of the examples of Rebinder effect in boundary lubrication can be given when considering friction and wear of copper alloys against steel in nonpolar mineral oil being nonactive to surface and in ils containing fatty acids or polar media like glycerine having active radicals in molecular structure.

Test procedure and parameters as well as characteristics of specimens are presented in Fig.5. Data on variation in friction coefficient, debris removal, debris size distribution as well as changes in structural state are presented in Figs 6-8. The clear difference in friction behavior is shown which can be explained by Rebinder effect reducing tensile stress which has a prominent value in fatigue wear. In case of inactive nonpolar oil friction coefficient decreases slowly and not so sharply as in case of active lubricant. Difference is taken place also if considering the debris generation which in case of inactive oil is not so intensive but involves much larger particles so the wear is much higher. Structural transformations are also have been obtained after friction in active lubricants as well as chemical changes in a thin surface layer of copper alloy as well as change in roughness (Fig.9).

Resuming the data related to the effect of surface-active components in boundary lubrication it should be mentioned that the optimum quantity of these components can provide mimimal wear at fast run-in.

Testing of Lubricants and Monitoring the Lubricated Units

Standard testing techniques of lubricants efficiency approved in most of industrial countries are mostly based on measurement of friction coefficient and evaluation of friction losses; estimation of load at which given friction coefficient or seizure occur; estimation of wear at given combination of load, velocity, and temperature; estimation of temperature at which the lubricant loses its performance. In USA, for example, there are two friction-related tests for greases and eight wear-related tests, - five for greases and three for oils (see Table 1). Most common machines for testing are four-ball machine and block-on-ring machine. In CIS standard are four-ball machine test (USSR Standard 9490-75) and ball against ring, roller and cone tests (USSR Standard 23.221-84).

Useful addition to common methods of lubricants testing can be the using of electrical and acoustic techniques providing information on boundary layer behavior on the contact. Even measurements under static loading can provide data on strength of lubricant layer in nanoscale (Fig.10) when plotting contact resistance against load. Scanning of lubricated surfaces by microprobes can give data on boundary layer strength at shearing and on the effect of a given lubricant on the oxide films on the metal surface (Fig. 11). Use of external voltage application to the lubricated sliding contact can simulate contact heating and provide the information on temperatures of lubricant chemical modification and failure (Fig. 12). The latter method can be used as a supplement to four-ball machine test in case of soft alloys and heterogeneous materials testing.

Monitoring of the lubricant behavior on the contact can be efficiently realized by acoustic emission measurements due to a good correlation of acoustic emission and friction performance. It can be illustrated by data presented in Fig. 14 for boundary lubrication of metal contact.

Analysis of lubricant can be quite useful addition to surface analysis as well as have independent value in monitoring lubricated system. General scheme of lubricant analysis is presented in Fig.15.

Debris analysis has become a popular issue in tribology community about 15 years ago. One of the developments accelerated its progress was an introduction of Ferrography, - magnetic deposition of particles from lubricant with further analysis of the sediment. Principle of a Ferrograph is shown on Fig.16. Microscopic observations are typically carried out after the sediment obtained in Ferrograph is fixed on the substrate like shown in Fig 17. Later Ferrograph has been modified in order to escape some disadvantages related to short path of sedimentation. Rotary Particle Depositor (RPD) has been designed in Swansea Tribology Center for this purpose. A scheme of this device is given in Fig.18. But the problem arising with devices like Ferrograph or RPD is a difficulty in obtaining quantitative data on wear mode and rate. To overcome this difficulty RPD has been supplemented by Particle Quatifier (PQ) which is based on magnetometric measurements of a sediment produced in RPD. PQ index has been used to characterize the particles of wear with magnetic properties content in the sediment. A number of other methods have been introduced from this time.They have used different physical principles related to contaminated lubricants, -magnetic, acoustic, light phenomena. Two examples of such systems are presented in Figs 19, 20. Ferrography has been also modified in order to use it in on-line systems (see Fig.21).

Research in the area of wear diagnostics has been carried out in MPRI staring in 80ies. It was mostly related to magnetic methods in combination with optical measurements. Some effects have been found for example change in the shape of lubricant contaminated by debris under the effect of light because of heat generation on the particles surface and convection in the layer of lubricant. Shape change gives possibility to measure quantitatively the degree of contamination by optical density of lubricant (see Fig.22).

The other principle has been put as basical for Opto-Magnetic Detector (OMD) scheme of that is given in Fig 23. This scheme includes sample of oil placed inside cylinder coil generating magnetic field,light source and light receiver. The principle of OMD operation is based on change in oil with debris optical density under the effect of magnetic field. There is a first reading obtained for contaminated oil in the beginning of measurements when the magnetic field is turned off. This reading gives information on total contamination content including magnetic particles (ferrous metals,their oxides and carbides) and nonmagnetic particles (products of oil ageing and oxidation, mineral particles like sand or dust, nonferrous metals and oxides). The second reading is obtained after the field is turned on. This reading provides information on the total content of magnetic particles in oil which are effected by field. The fird reading is obtained after the field is switched off. this reading is related to magnetic particles of large size. So the OMD provides three quantitative parameters important in evaluation of oil state and also state of the machine friction unit.Possible development of OMD principle can be the on-line device installed in lubricant circulation system.

Condition monitoring is considered to be an efficient tool in providing operation efficiency of machinery, reducing the cost of maintenance, saving materials, energy and labour. The whole concept is based on combination of diagnostic devices, on-line monitoring systems, tracking the data on machine operation and making recommendations based on the knowledge accumulated in database. Final goal of the concept is a monitoring system combined with the expert system made necessary corrections in operation conditions or other maintenance measures.

There are certain examples of condition monitoring applications in industry. One of them is a Swansea Laboratory Services which provides condition monitoring for heavy machinery placed on the sea oil rigs. Structure of the service is shown schematically in Fig.24.

It includes data collection on the rigs at certain time intervals established for each type of machines (gear transmissions, engines etc), supply of samples to laboratory, preliminary screening of samples and comparison of the data to computer track data on this particular equipment, additional analysis in case of some deviations of current data from common trend. Data accumulation, storage and processing is carried out using PC. The service is now include also section dealing with ground vehicles like intercity buses and because of the confirmed efficiency in failure prediction and cost reduction these services can be a good example of condition monitoring applications. The creation of an expert system for that service is in the beginning stage now.

New industrial trends and tribology

New fastly growing areas of industry have become more and more visible in recent years. These areas are related to new scale in engineering including micro- and nanoscale. One of the examples of such industries is magnetic storage of data in electronics which has become a significant sector of industry with billion of dollars turnover in the area of hard disc drives. The other example are precision units for fine positioning in robotics operating with microdisplacements. The whole new area called mechatronics has been established as a synthesis of mechanics and electronics. Booming electronics and optoelectronics request advanced machining operations and advance manufacturing such products as microchips, fiberoptics, microgears etc. Appearance of such nanoscale tools as Scanning Tunnel Microscope and Atomic Force Microscope create possibility of nanoscale design of materials including possibility to combine atomic structures by mechanical way.

Progress in aerospace industry requested precise rolling bearings, self-lubricated bearings to operate in outer space, gyroscopes with minimal friction losses,efficient noncontact seals and many other advanced design and manufacturing developments.

There is a lot of tribological problems in areas mentioned. For example the crucial point in magnetic storage systems is the decrease in operating clearance between head and disc as well as providing smooth and low friction at start and stop of head flight. The manufacturing of precise ceramic ball bearings for space applications needs new tecnologies of machining resulting in high accuracy in surface shape and roughness and this problem is solved when using abrasive machining in magnetic fluids. The number of such examples can be large an any area of modern high-tech industry.

Tribological benavior of magnetic storage devices is very complicated because it is necessary to meet contradictory requirements of low friction and wear, high stability of friction coefficient, independence of contact performances on breaks in operation, ambient media and many other factors. From the point of view of scale factor these systems are on the edge between micro- and nanoscale effects because the processes take place on very smooth surfaces where the atomic and molecular interactions take place. Presence of lubricant forming monomolecular layers or sandwiches of different origin adds other factors including capillary forces, viscosity in boundary layers, chemosorption etc. Because of the complexity in tribological behavior the optimum solutions should be found to meet the operation requirements. For example such optimum solution takes place in case of choosing the surface roughness. Fig.25 illustrates this fact showing the existence of optimum roughness decreasing the adhesion forces and at the same time providing relatively small area area of contact reducing deformational component of friction force.

The optimum solutin takes place in case of lubrication which fact is illustrated by Fig.26 where the effect of polarity and lubricant film thickness on friction is shown. The optimization of lubricant thickness, molecular weight, and viscosity results in the concept of dual lubricant layer with polar lubricant with reactive groups is placed on the disc surface and nonpolar lubricant is laid over this layer. Lower layer provides low friction in starting, good protection of surface in storage while upper layer provides low kinetic friction and protection of lower layer. Perfluoroethers are typical compounds used in these applications.

Among many tribological units are numerous rotating seals used to separate different working media. One of the modern approach in these systems is the application of magnetic fluids retained in a given place by magnetic forces. these fluids combine the properties of the efficient seal with low-friction hydrodynamic bearing. A typical scheme of magnetofluid seal is presented in Fig.27. The MF itself is a so-called "smart" material adjusting properties to change in ambient conditions. In case of seal the colloidal particles of magnetic material retained in magnetic field of permanent or electromagnet also keep its fluid carrier in the given place providing sealing effect. Application of MF include friction clutches, brakes and other tribological units used in motion transfer or control.It is interesting to mention that using of magnetic fluids has started in seals for space applications where cost efficiency was not a first priority. With the development of MF production technology and reducing a cost of fluids many other applications in industry have become possible. Fof example fine machining of ceramic balls for rolling bearings was reported when using abrasive slurry mixed with MF and suspended by non-magnetic pad (Fig.28).

The new "smart" material used in advanced design is the electrorheological fluid (EF). This fluid can change its properties under the effect of electric field creating a fast responce to electrical signal. A schematic design of EF clutch is shown in Fig.29.

For some estimates the potential market for EF applications can be about 20 billions dollars mostly in automotive transmissions. EF have some advantages compare to MF because the range of materials in that case is much wider and possible shear stress limit is much higher which is important from point of view of motion transfer.

The challenging area for advanced tribological design is the high-temperature engine tribology. The concept of this engine now is well developed and the appropriate materials have been found among such ceramics as silicon nitride and silicon carbide. One of the serious problems was a lubrication of such an engine at temperatures above 500-700 C. One elegant solution to this problem has been proposed when using the engine exhaust gases as a lubricant for engine bearings. The effect is based on the transformation of exhaust gases to amorphous or microcrystalline carbon which has a good lubricating performances for ceramic parts. The carbon film is replenished on the working surfaces as newly injected gas nears the heated friction contact.

Main Problems in Tribology Research

The global value of tribology research and development can be roughly evaluated from the following figures. According to estimates of experts total losses of energy, materials, human labour and losses due to ecology problems related to tribology can be estimated as 5 to 10 percents of GNP in industrial world. Which is most important a significant part of these losses can be saved at modern level of tribolocical knowledge only due to technology transfer from science to industry.

International Tribology Council which join the national tribology societies of the most industrial countries has formulated a number of problems should be solved untill the 50th anniversary of Tribology definition as a discipline.

They are as follows:

In the area of materials

- lubricants efficient at high temperatures up to 750 C, at radiation conditions, in vacuum, lubricants compatible with biological objects and pure from the point of view of ecology

- lubricants for metal hot forging

- lubricants for extreme conditions including units operating with liquid nitrogen or oxygen

- selflubricated polymers and ceramics

- materials for high-loaded friction units not requiring maintenance

- composite materials combining high strength, heat and electric conductivity

In the area of surface treatments

- advances in deposition of selflubricated coatings and hard facings

- high-energy surface modification and chemical modification

- application of nanolayer lubricants

In the area of tribosystems design and calculation

- formulas for long life prediction and simulation of the tribosystems

- design of magnetic levitation units

- design of perfect seals especially for biochemistry

- units for precision engineering and mechatronics

- condition monitoring systems

- acoustic and acoustic methods

In the area of basic concepts

- universal concept of boundary lubrication

- information storage and processing for use in tribology
- concept of tribosystem ecological compatibility

The list of above-mentioned topics is not closed yet and national societies should complete it for consideration of tribological community. So, it will be a lot of job for next generation of tribologists.

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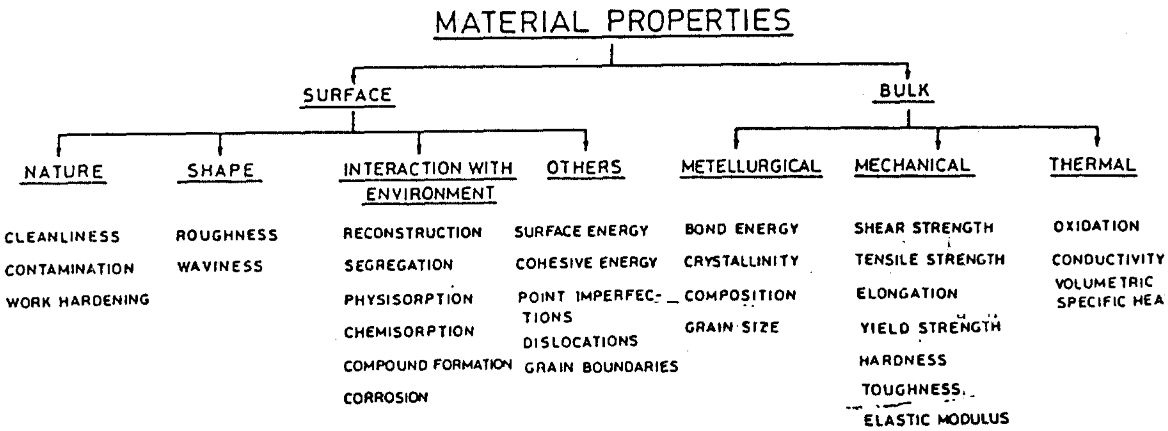


Fig.1. Surface properties relevant to tribological behavior of materials (Bhushan)

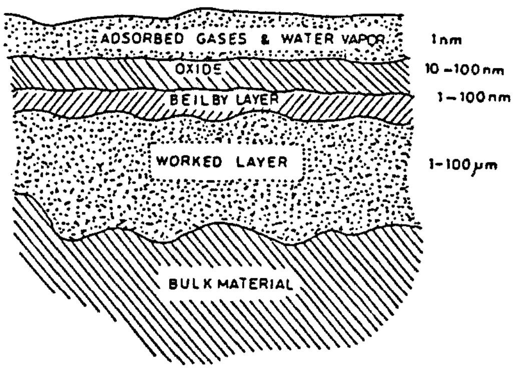


Fig.2. Schematic representation of a metal surface (Bhushan)

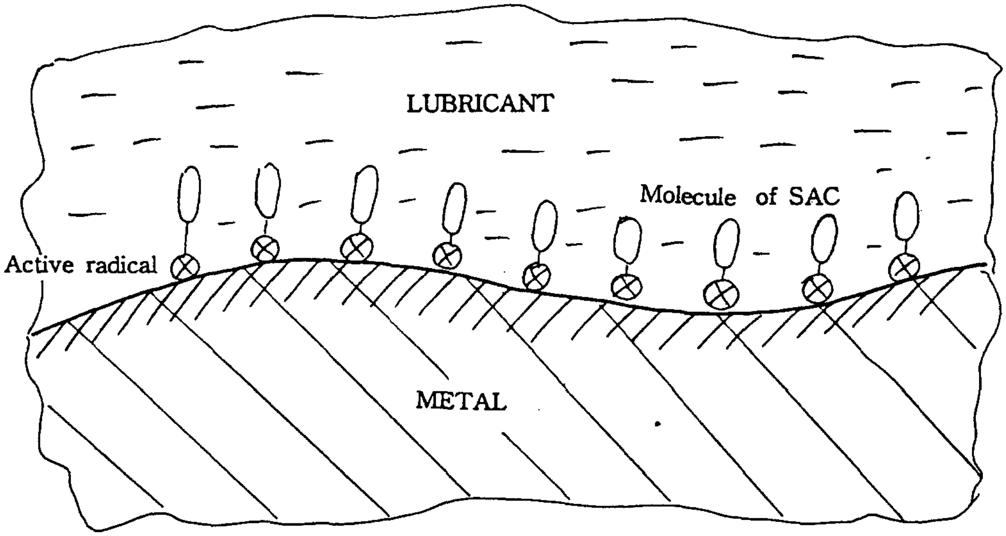


Fig.3 Adsorption of surface-active compounds in lubricant on the metal surface

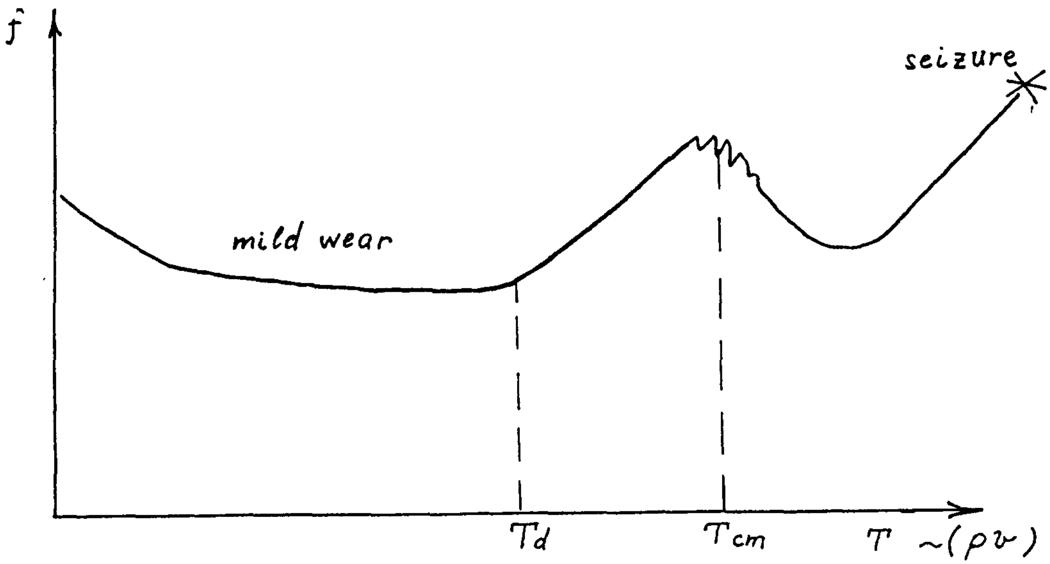


Fig.4. Behavior of boundary lubricant layer at frictional heating in the presence of chemically-active additive: Td - temperature of lubricant layer disorientation, Tcm - temperature of chemical modification

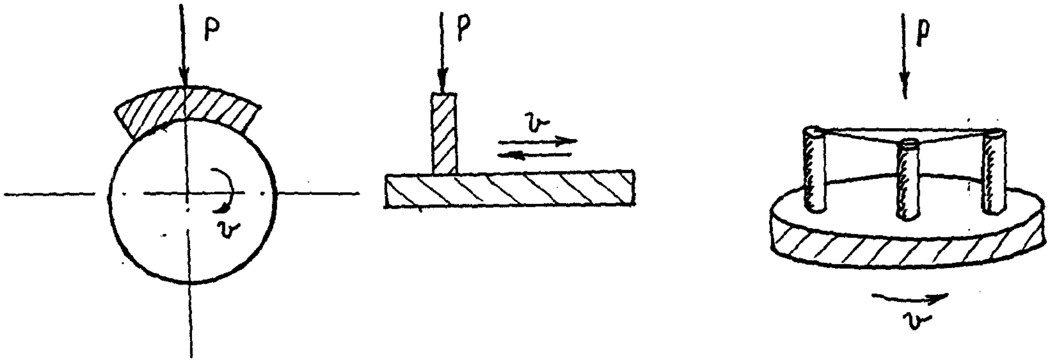


Fig.5. Testing schematics and specimens: lower specimens - steel, upper specimens - bronze; lubricant - paraffine oil, oil + fatty acid, glycerine

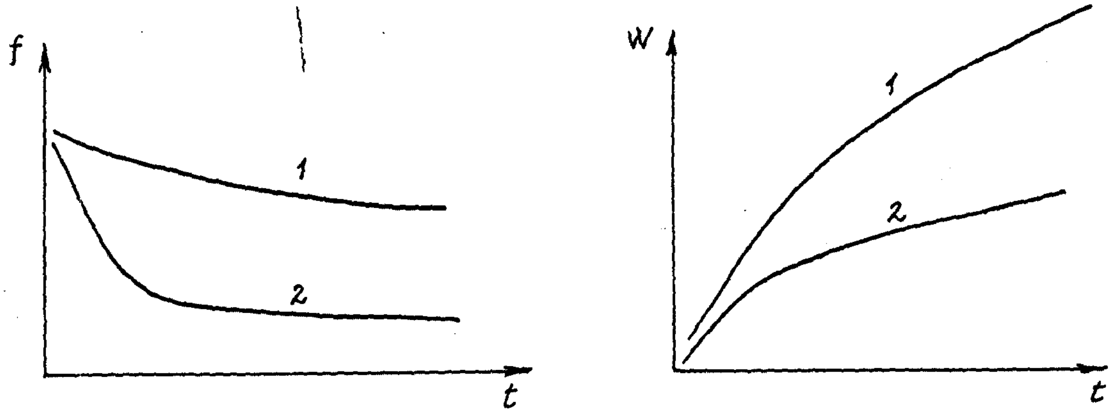


Fig.6. Friction performance at boundary lubrication of bronze against steel: 1 - inactive oil, 2 - surface-active lubricant

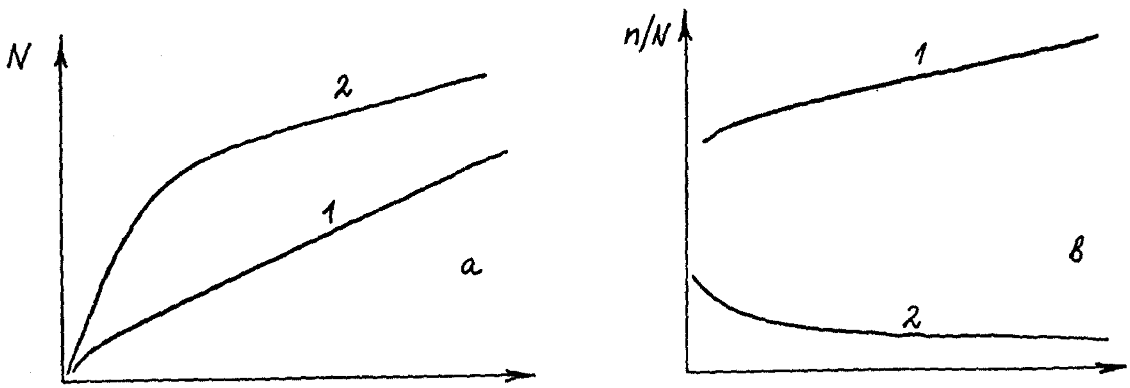
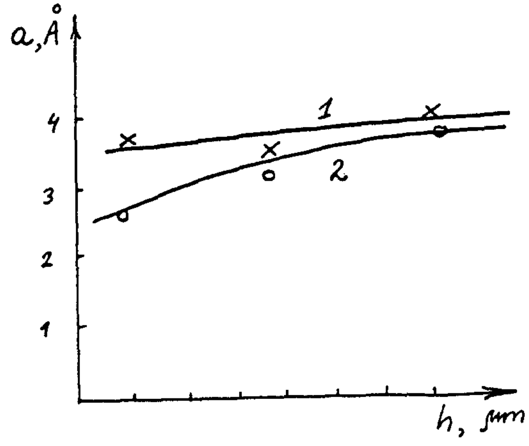


Fig.7. Total number of debris in a unit volume of lubricant (a) and ratio of large particles number to total number (b) when testing in inactive (1) and surface-active lubricant (2)



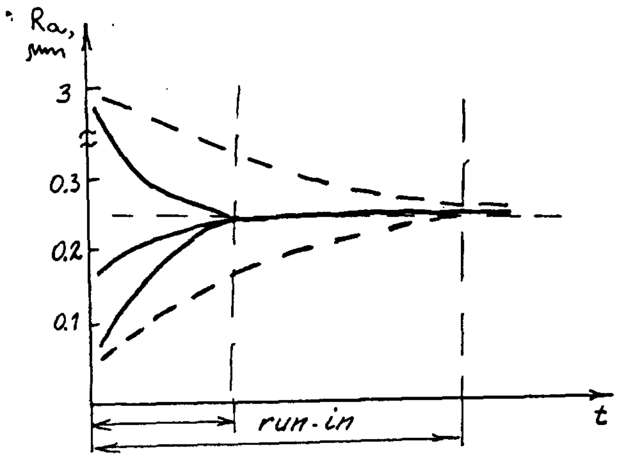


Fig.8. Lattice parameter of copper specimen vs. depth of surface layer after friction against steel in inactive (1) and surface-active (2) lubricant

Fig.9. Formation of equillibrium roughness characteristic for given conditions of run-in in inactive (broken lines) and surface-active (solid lines) lubricants

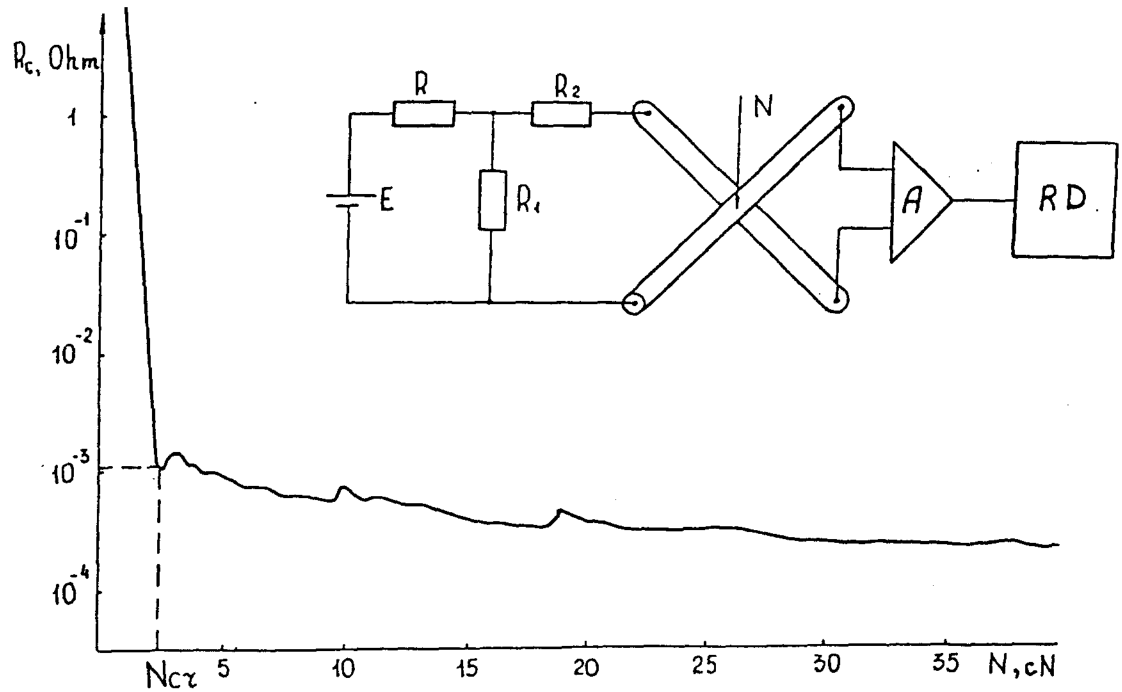


Fig.10. Determination of boundary layer strength when measuring contact resistance as a function of nomal load: E - stabilized current source, R - resistor, A - amplifier, RD - recording device.

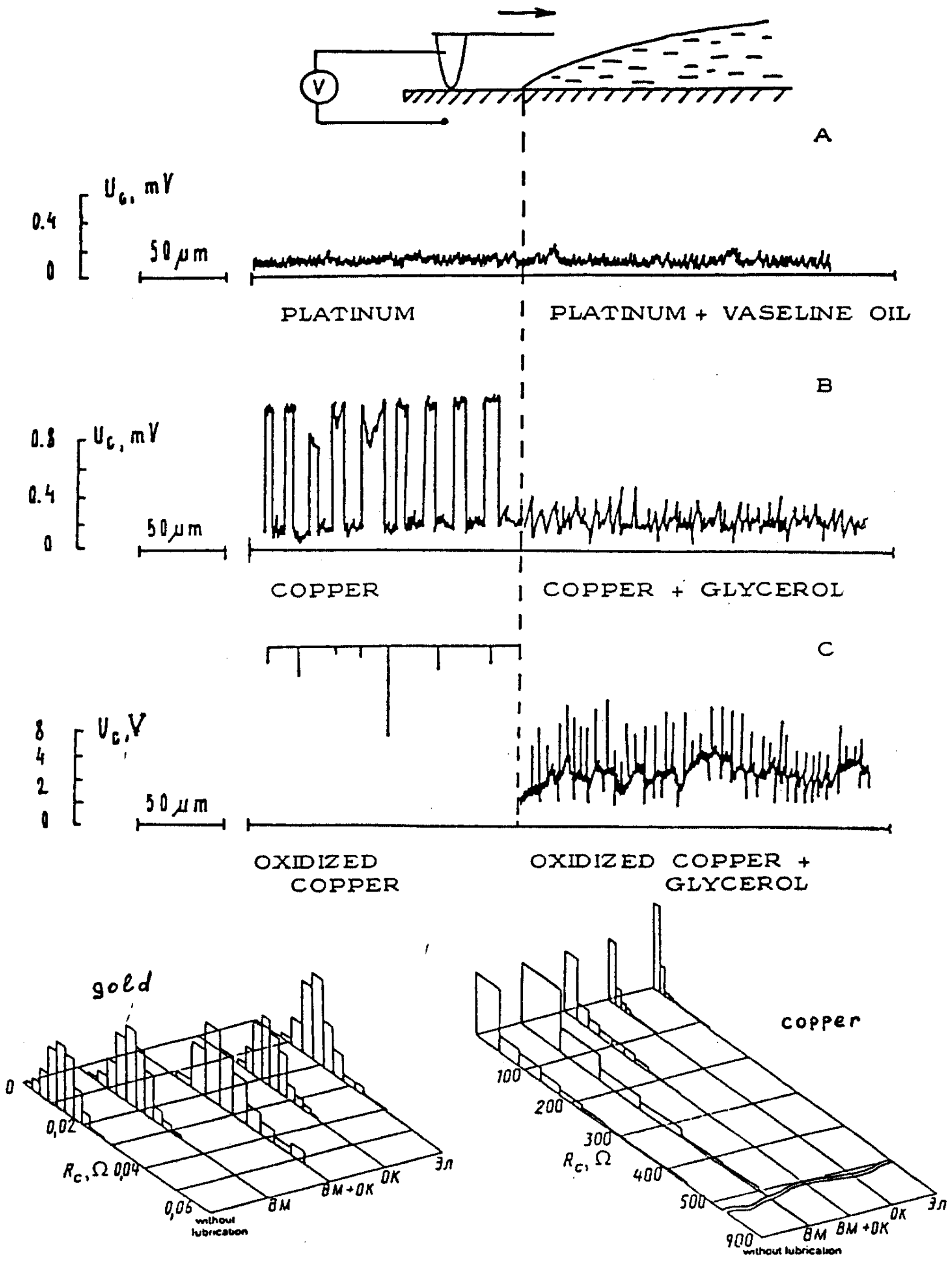


Fig.11. Contact voltage drop when scannig the lubricated surface by conductive microprobe

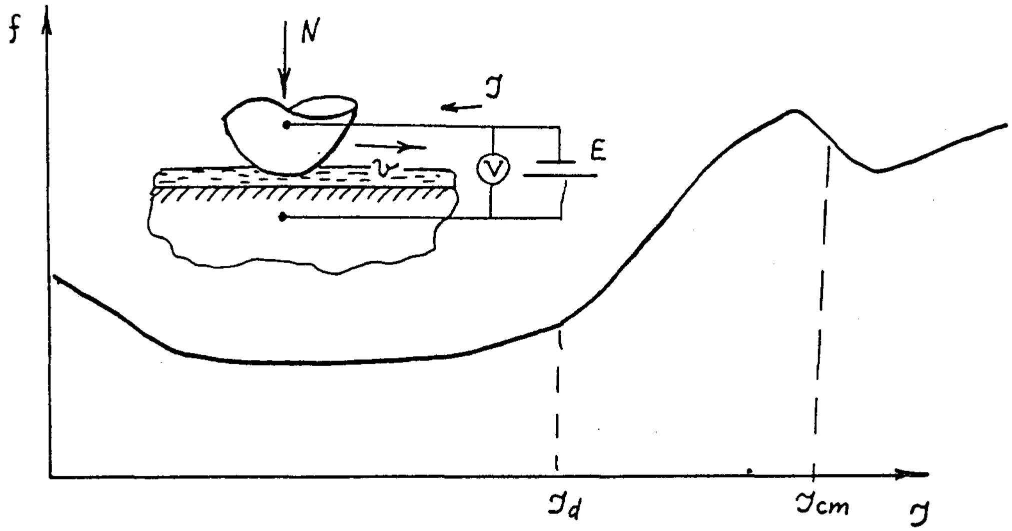


Fig.12. Application of electrical current to simulate boundary layer behavior at frictional heating: Jd - current related to temperature of layer disorientation, Jcm - current related to chemical modification temperature

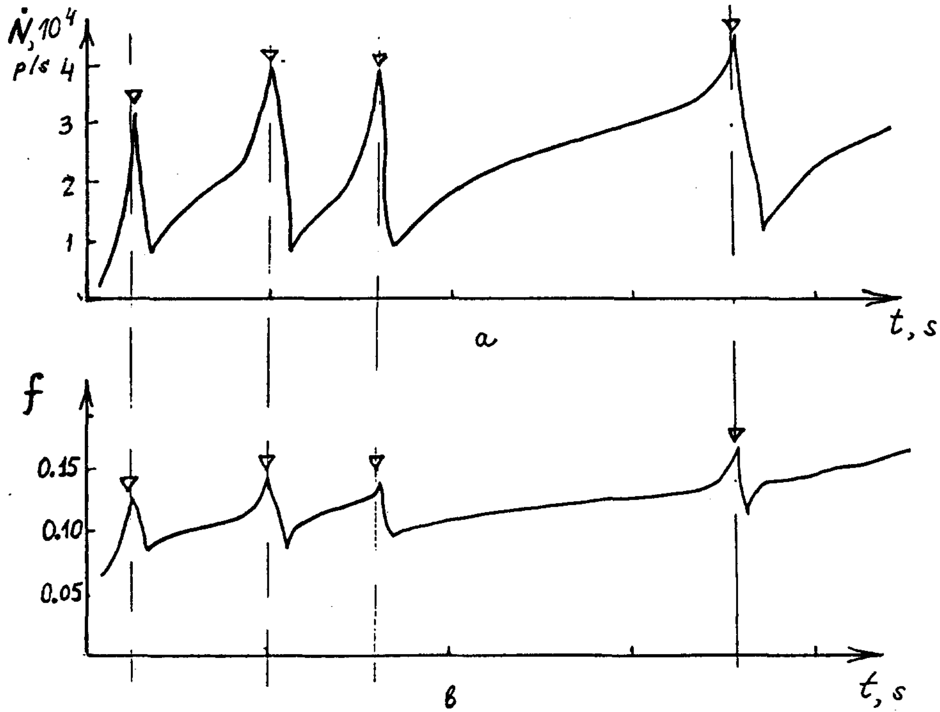


Fig.14. Rate of acoustic emission (a) and friction coefficient (b) plotted against time of friction in metal contact: triangles are related to lubricant feed in the contact

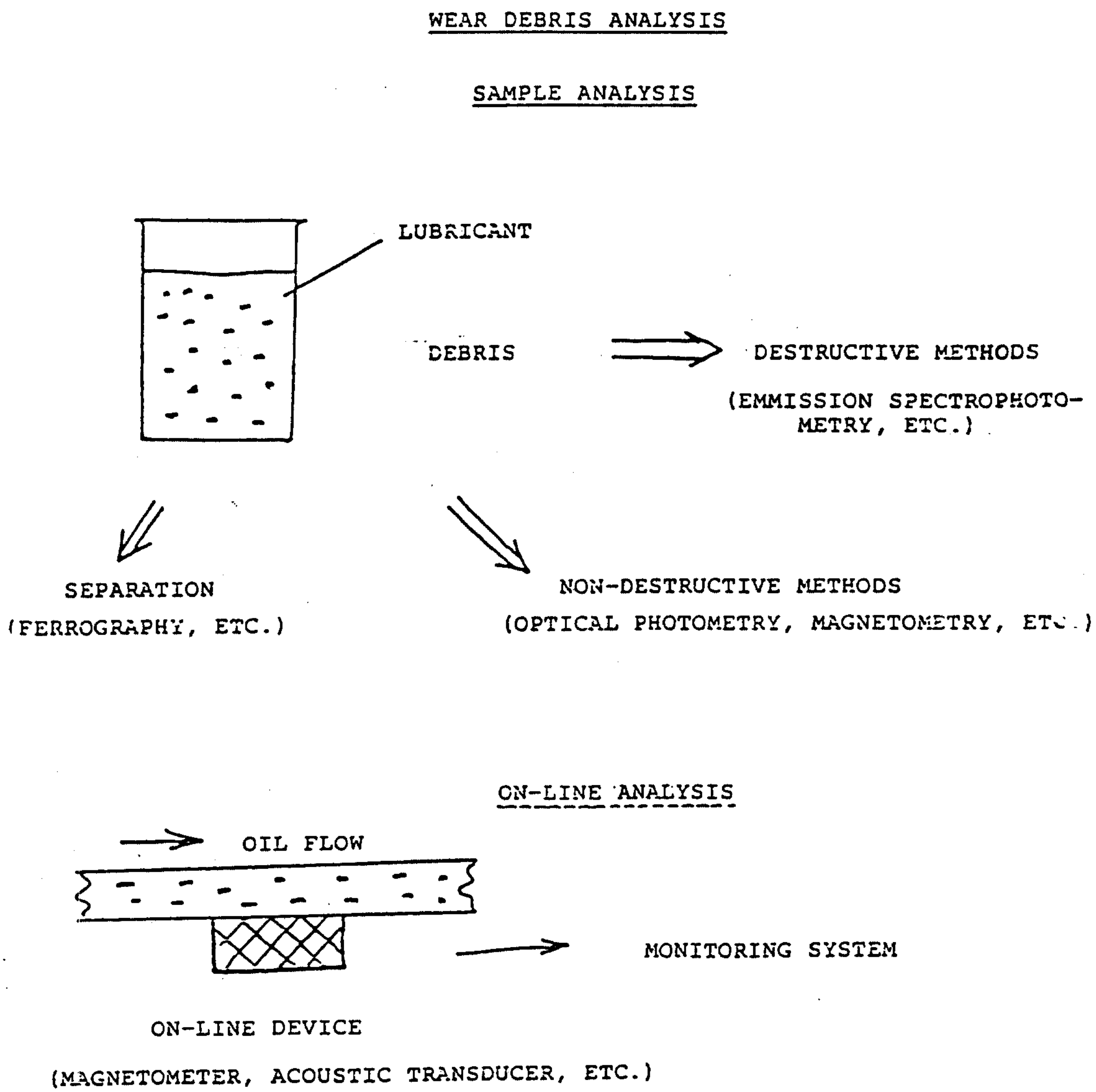


Fig.15. General scheme of lubricant analysis

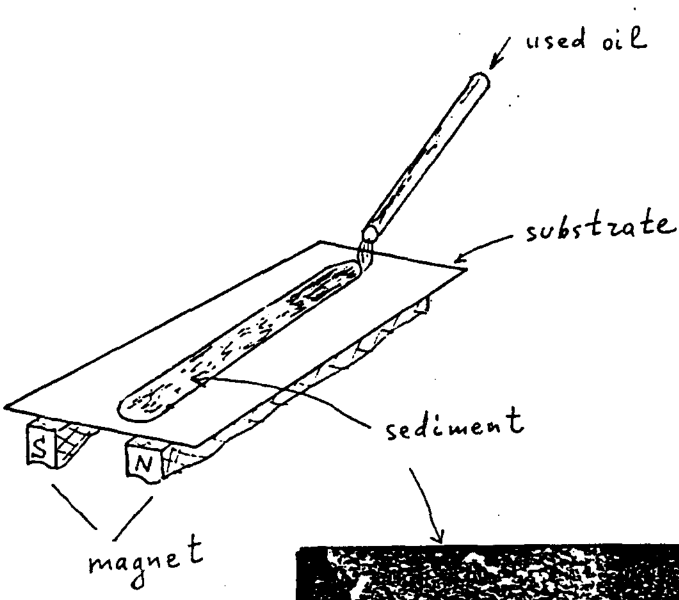


Fig.16. Schematic of Ferrograph

Fig.17. Debris sedimented on a substrate

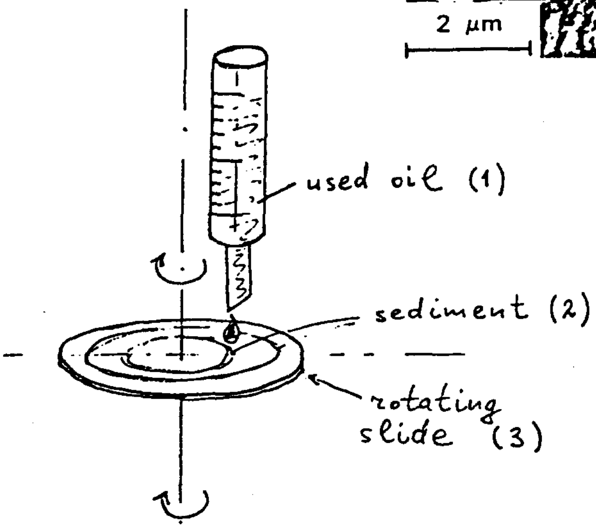


Fig.18. Schematic of Rotary Particle Depositor: 1 - used oil, 2 - sediment, 3 - rotary slide

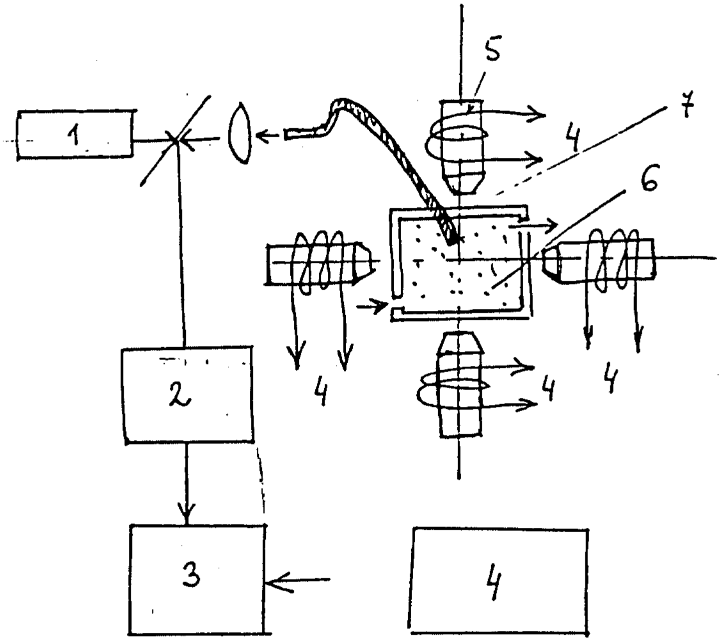


Fig.19. System for on-line monitoring of debris in oil: 1 - laser, 2 - transducer, 3 - microprocessor, 4 - control unit, 5 - magnet, 6 - cell, 7 - optic fiber

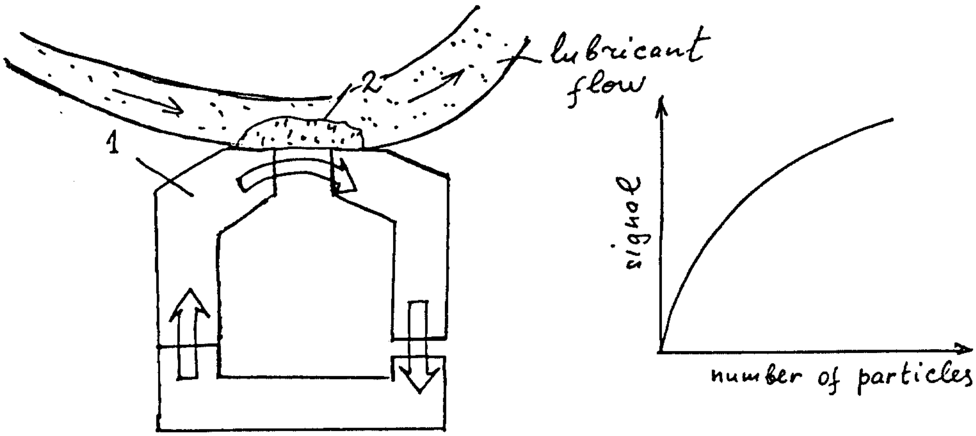


Fig.20. System for on-line monitoring the oil by magnetic sencor: magnetic head, 2 -debris build-up

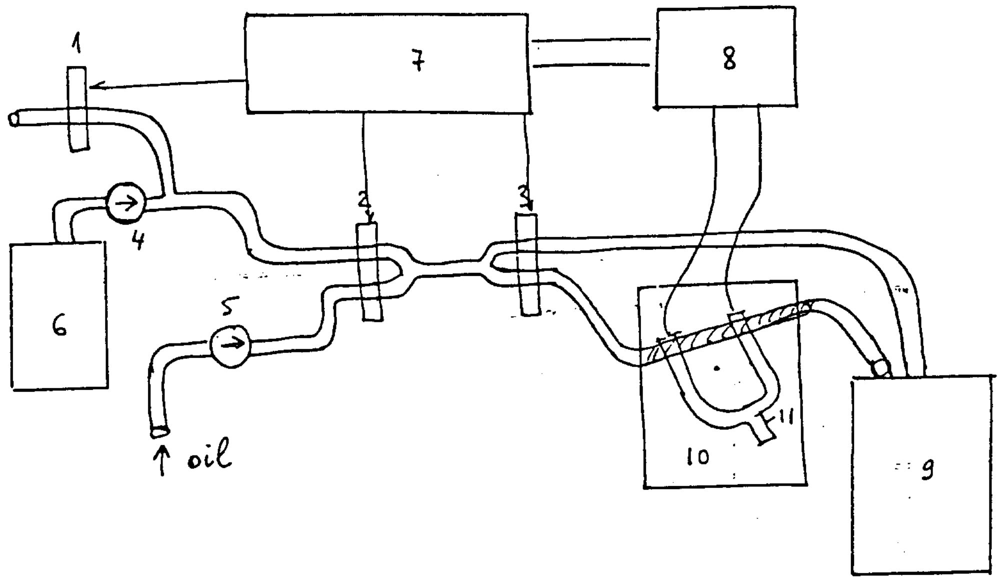


Fig.21. Schematic of on-line Ferrograph: 1,2,3 - valves, 4,5 - membrane parts, 6 - solvent, 7 - microprocessor, 8 - transducer, 9 - reservoir, 10 - ferrograph, 11 - light source

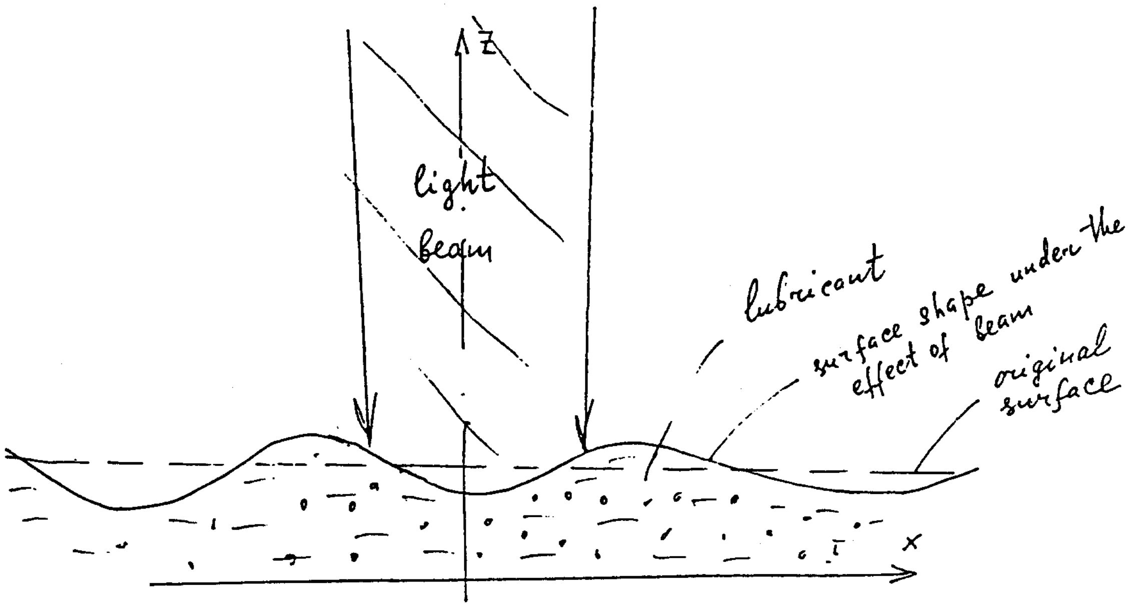


Fig.22. Change in shape of used oil surface under the effect of a light beam

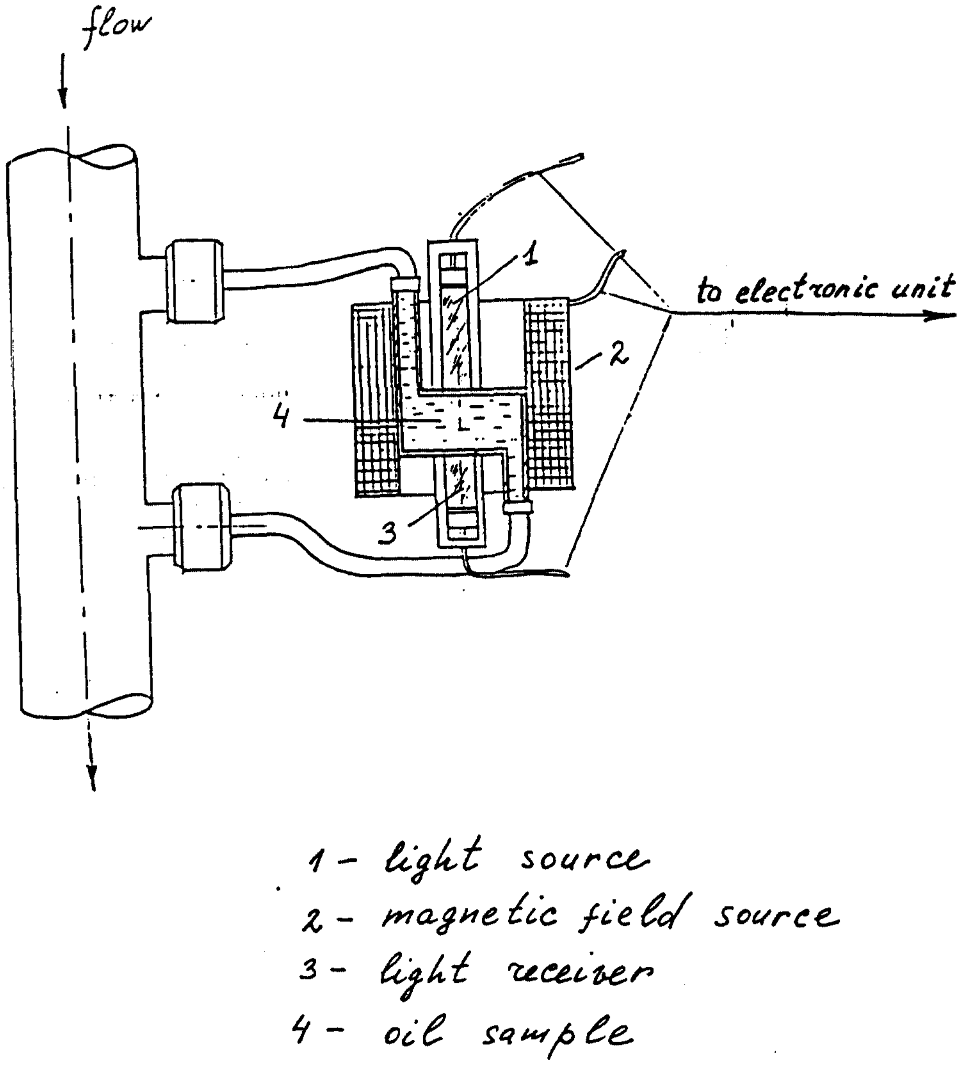


Fig.23. Principal schematic of the Optomagnetic Detector

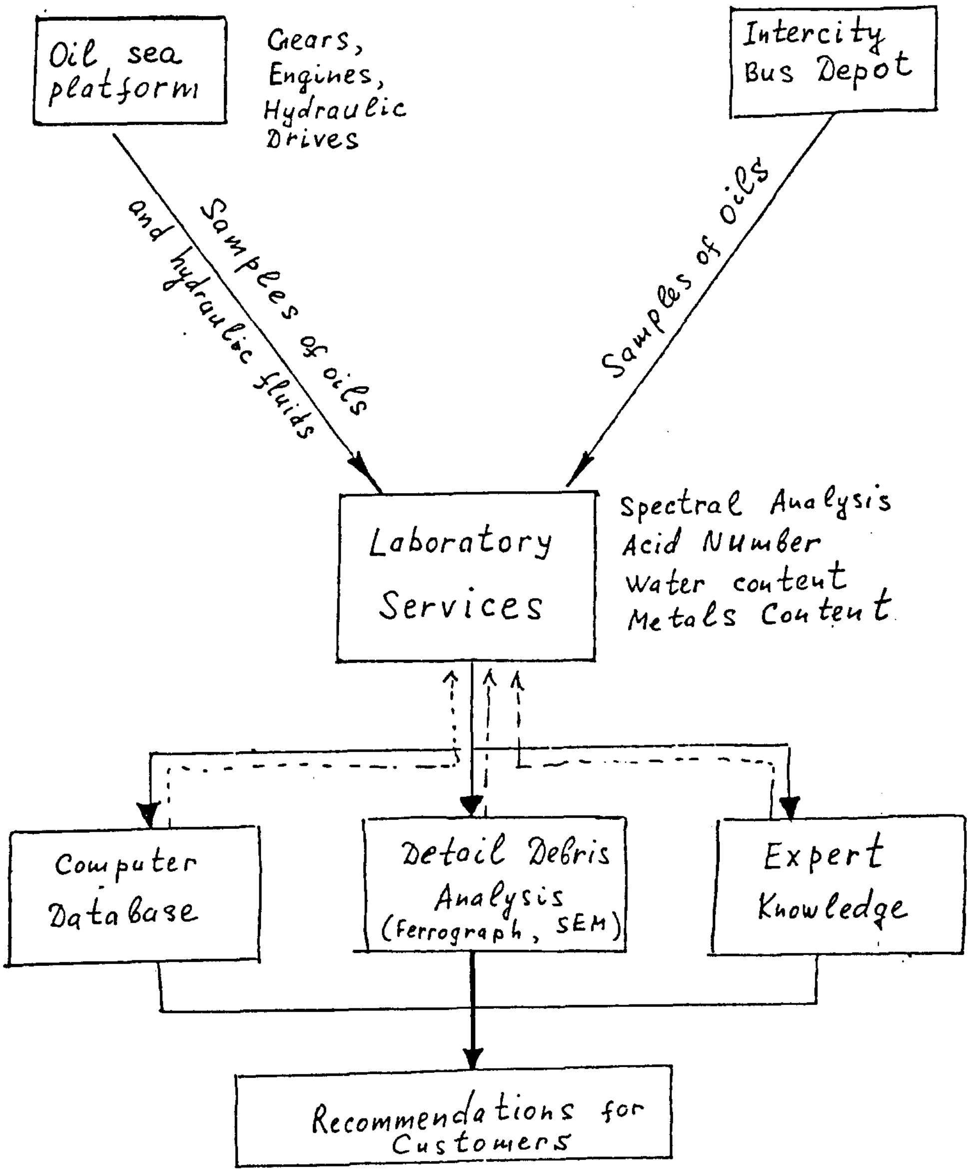


Fig.24. A structure of Condition Monitoring Services

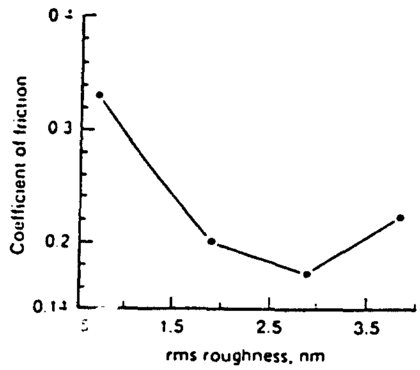
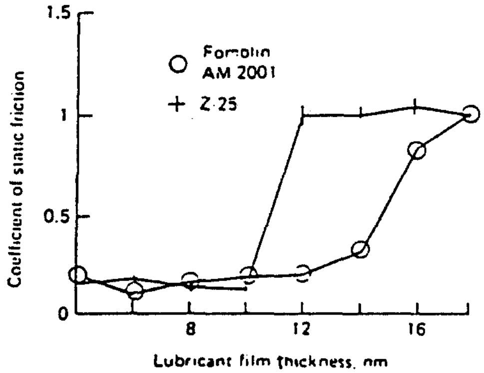


Fig.25. Coefficient of friction as a function of surface roughness for magnetic disk drive (Bhushan)



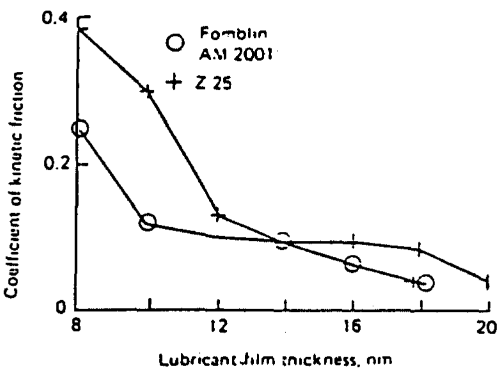


Fig.26. Static and kinetic friction coefficients as a function of lubricant film thickness for polar (AM 2001) and nonpolar (Z 25) perfluorpolyethers (Bhushan)

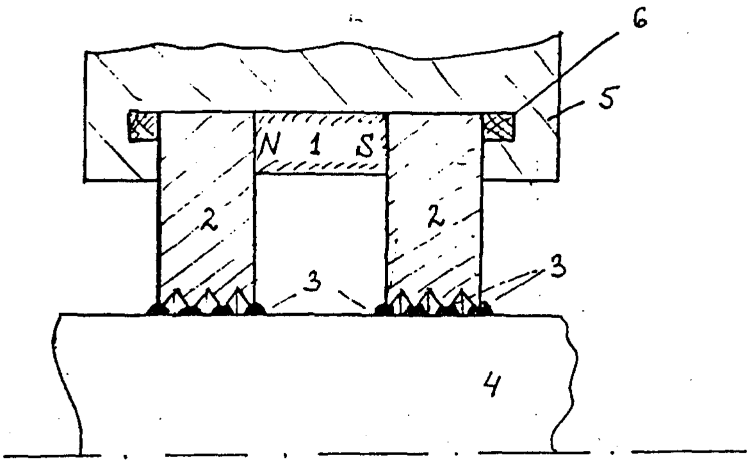


Fig.27. Schematic of magnetofluid seal: 1 - permanent magnet, 2 - poles, 3 - magnetic fluid, 4 - shaft, 5 - housing, 6 - sealing gasket

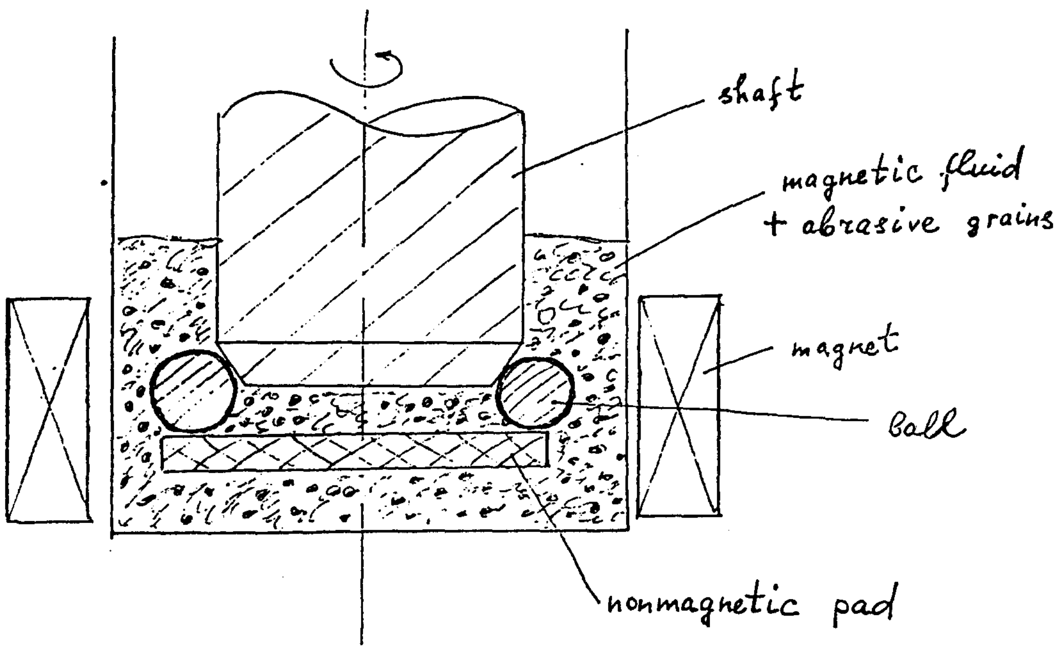


Fig.28. Schematic of fine polishing of ceramic balls (Kato)

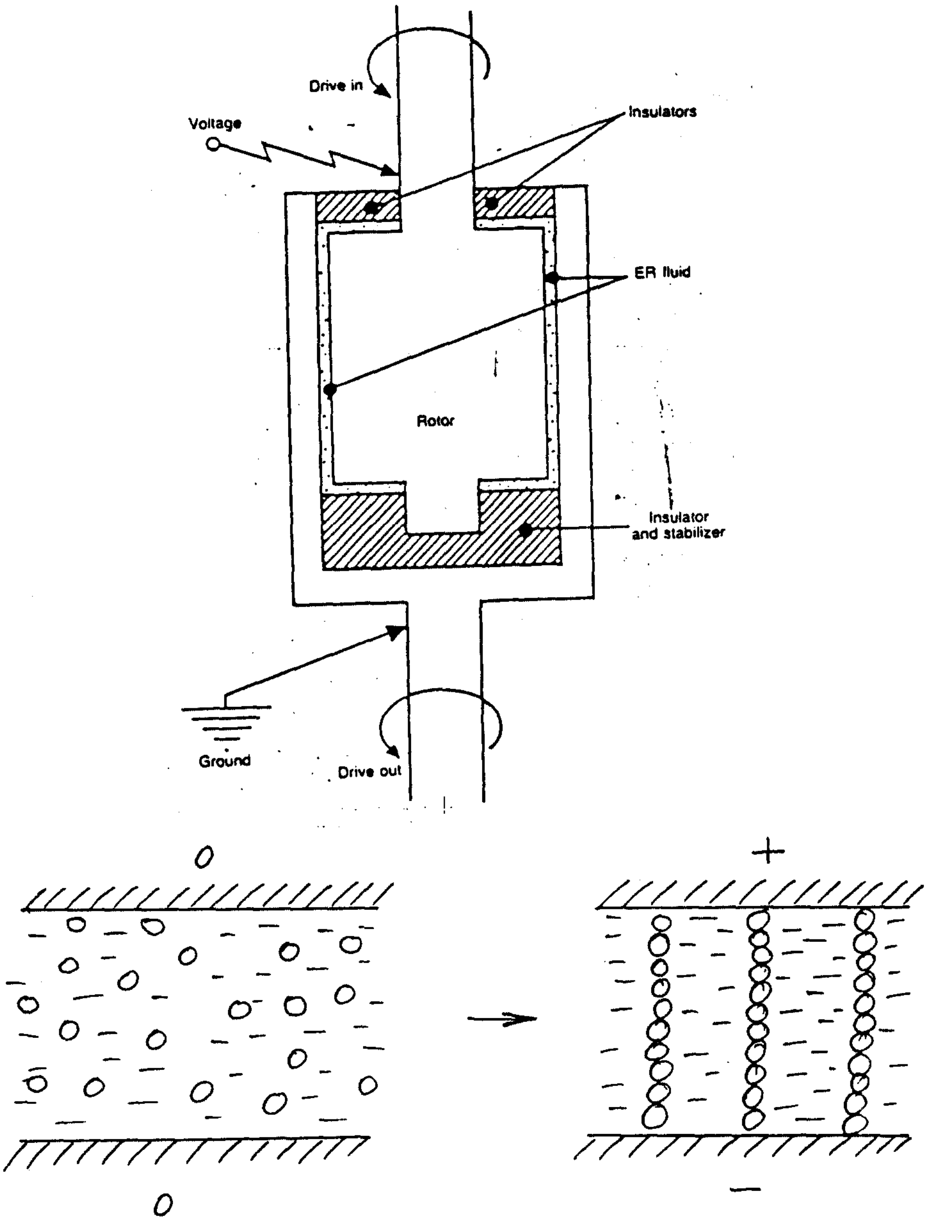


Fig.29. Principal design of a clutch with electrorheological fluid