МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
АЕРОКОСМІЧНИЙ ФАКУЛЬТЕТ
КАФЕДРА ПІДТРИМАННЯ ЛЬОТНОЇ ПРИДАТНОСТІ ПОВІТРЯНИХ СУДЕН

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач кафедри
канд. техн. наук, доц.
_______________О.В. Попов
«_____»_____________2021 р.

КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ЗДОБУВАЧА ОСВІТНЬОГО СТУПЕНЯ МАГІСТРА
ЗА ОСВІТНЬО-ПРОФЕСІЙНОЮ ПРОГРАМОЮ
«ТЕХНІЧНЕ ОБСЛУГОВУВАННЯ ТА РЕМОНТ ПОВІТРЯНИХ СУДЕН І АВІАДВИГУНІВ»

Тема: «Аналіз зносостійкості авіаційних матеріалів з титановими сплавами»

Виконав: __________ **Хасан Фалах Хасан Аль-Рубайє**

Керівник: канд. техн. наук, доц. __________ **Ю.І. Смірнов**

Консультанти з окремих розділів пояснювальної записки:

охорона праці: канд. біол. наук, доц. __________ **В.В. Коваленко**

охорона навколишнього середовища: д-р. пед. наук, проф. __________ **Т.В. Саєнко**

Нормоконтролер __________

Київ 2021

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
NATIONAL AVIATION UNIVERSITY
AEROSPACE FACULTY
AIRCRAFT CONTINUING AIRWORTHINESS DEPARTMENT

PPERMISSION TO DEFEND
Head of the department
Ph. D., Assoc. Professor
_____________ O. V. Popov
«____”_______________ 2021

MASTER`S DEGREE THESIS

(EXPLANATORY NOTE)

GETTER ACADEMIC MASTER DEGREE

FOR EDUCATIONAL-PROFESSIONAL PROGRAM
«MAINTENANCE AND REPAIR OF AIRCRAFT AND AVIATION ENGENS»

Topic: «Analysis of wear resistance aviation materials with titanium alloys»

Created by: ___________**Hasan Falah Hasan Al-Rybaye**

Supervisor: Ph. D., Assoc. Professor ___________**Y.I. Smirnov**

Advisers on Individual Sections:

Labour precaution:
Ph. D., Assoc. Professor _____________**V.V. Kovalenko**

Environmental protection:
Ed.D. Professor _____________**T.V. Sayenko**

Standards Inspector: _____________

Kyiv 2021

NATIONAL AVIATION UNIVERSITY

Faculty: Aerospace faculty
Aircraft Continuing Airworthiness Department
Educational and Qualifications level: «Master Degree»
The specialty: 272 «Aviation transport»
Educational-professional program «Maintenance and Repair of Aircraft and Engines»

PPERMISSION TO DEFEND
Head of the department
Ph. D., Assoc. Professor
_____________ O. V. Popov
«____”_______________ 2021

Task

for diploma work performance of master
HASAN FALAH HASAN AL-RYBAYE

1. Work theme: « Analysis of wear resistance aviation materials with titanium alloys » approved by rector order № 2196/ст of October 11, 2021.
2. Work execution period: since October 25, 2021 until December 31, 2021.
3. Initial data for the project: Analysis of details damages produced from titanium alloys in couple with other metals
4. The content of the explanatory note (the list of problems to be considered): The brief description about airplane designed parameters and substantiation of the engine working process parameters; analysis of details damages from titanium alloys in aviation; determination methodology of specimen wear, investigation results regarding titanium alloy BT-22 in couple with other aviation materials;
5. The list of mandatory graphic materials: analysis of details damages from titanium alloys in aviation, titanium alloys application in aviation, testing methodology, determination methodology of specimen wear, investigation results regarding titanium alloy BT-22 in couple with other aviation materials, fractographical tests of surface friction, conclusions and recommendations

6. Time and Work Schedule

	Stages of Graduation Project Completion	Stage Completion Dates	Remarks
1	Analysis of titanium alloys damages in couple with other materials	25.10.2021-28.10.2021	
2	Determination of experiment methodology and samples choosing	29.10.2021 – 02.11.2021	
3	Providing experiments regarding fretting characteristics	03.11.2021 – 10.11.2021	
4	Analysis of obtained results based on damages	11.11.2021 – 15.11.2021	
5	Designing chapters of explanatory note	16.11.2021 – 20.11.2021	
6	Preparing chapters “labour precaution” and “ecological safety”	21.11.2021 – 04.12.2021	
7	Projecting graphical material and presentation	05.12.2021 - 20.12.2021	

7. Advisers on individual sections of the work (Thesis):

Section	Adviser	Date, Signature	
		Assignment Delivered	Assignment Accepted
Labour precautions	V.V. Kovalenko		
Environmental protection	T.V. Sayenko		

8. Assignment issue date «___» _____________ 2021

Thesis supervisor: _____________ Y.I. Smirnov

Assignment is accepted for performing _____________ Hasan Falah Hasan Al-Rybaye

ABSTRACT

The explanatory note to master's degree work « Analysis of wear resistance aviation materials with titanium alloys » contains

101 pages, 36 Fig's, 5 tables, 47 literature sources.

Object of study is wearability of titanium alloy BT-22 in couple with other aviation materials.

Subject of study is processes of wearing of titanium alloy BT-22 in couple with other aviation materials.

The purpose of degree work is determination of optimal couple while wearing titanium alloy in couple with other aviation metals.

Research method - laboratory studies of the wear mechanisms of the parts made of titanium alloy BT-22 and other aviation steels and metals in sliding friction.

The complex analysis of the methods for details restoration was conducted. The complex study on qualitative and quantitative parameters of mating surfaces friction, tests on the special machine MFK-1 that imitates cycles of details wear.

All these issues are described as fully as possible, thesis is completed in accordance with all requirements of the degree works fulfillment, the specifics of specialty is taken into account.

This degree work contains results that help to understand the necessity of using the right metals and metal alloys in couple with titanium alloy BT-22. Such clear analysis will help to design cheaper details with less primecost and with longer operational term and high reliability at the same time. This work was directed for solving exactly these problems.

FRICTION, SLIDING, SURFACE COVERAGE, HARDNESS, TITANIUM, LINEAR WEAR, ALUMINIUM, OXIDES, FRETTING, CORROSION.

LIST OF ABBREVIATIONS

APS – air plasma spray

BACT – best available control technology

CAA – clean air act

CMC– ceramic-matrix composites

CTE - coefficient of thermal expansion

EBPVD – electron beam physical vapor deposition

ESAVD – electrostatic spray assisted vapour deposition

HCP - hexagonal close-packed

HEPA – high-efficiency particle absorption

HVOF - high velocity oxygen fuel

MACT – maximum achievable control technology

NAAQS– national ambient air quality standards

PTWA - plasma transferred wire arc

RCRA – resources conservation and recovery act

SCC - stress-corrosion cracking

SPPS – solution precursor plasma spray

TBC – thermal barrier coatings

USZ – ultra-stabilized zirconia

CONTENTS

INTRODUCTION

To begin with I want to mention that every element has its own life cycle. No matter if it corresponds to elements made by human or some naturally created parts. Though speaking about details that are created for different movement purposes the lifecycle runs much faster. The reason for that is that such details are under great influence of friction forces and hence wear becomes the reason why their lifecycle is so short.

Among the maing negative factors that can damage different details is fretting-corrosion. No matter what are the modern methods of repairing and recovery, but unfortunately all of the details that are under cyclic movement cannot avoid its influence.

So the way out is to use such materials and especially alloys that can reduce losses of surface and elongate duration of details operation. In our diploma work we will make a set of tests on the special machine that imitates cyclic movement. For obtaining the best results that are close to reality we chose titanium alloy BT-22 in couple with different materials and try to compare our important results. Due to this results we will understand the best and most reliable couple for titanium alloy. It’s obvious that titanium is very reliable element and has very high characteristics. So we will try to find out the best metal alloy among the counter specimens.

Our investigations will be very useful for different plants, factories and design offices. We will determine the best couple that corresponds to 2 main parameters: prime cost and durability.

Basically landing gear elements consist of elements which are originally from couple of titanium alloys and some colored metals. So in our diploma work we will discuss couple combinations that can be applied in landing gear design, because LG requires high quality, long operational time and low primary cost. It can be explained due to reason that landing gear elements are responsible for flight safety during such procedures as landing and takeoff.

PART 1.

DAMAGE ANALYSIS OF TITANIUM ALLOYS DETAILS IN AVIATION

1.1 Titanium alloys application

The primary attributes that make titanium an attractive material include an excellent strength-to-weight ratio, providing weight savings attractive to the aerospace and petrochemical industries; corrosion resistance, particularly appealing to the aerospace, chemical, petrochemical and architectural industries; and biological compatibility, of interest to the medical industry. The chemical industry is the largest user of titanium due to its excellent corrosion resistance, particularly in the presence of oxidizing acids. The aerospace industry is the next largest user, primarily due to its elevated (and cryogenic) temperature capabilities and weight savings due to its high strength and low density; with increased use of polymeric graphite fiber reinforced composites on aircraft, the low coefficient of thermal expansion is also an important factor. The ballistic properties of titanium are also excellent on a density-normalized basis. Highlights of titanium applications in other areas will be briefly discussed.

1.1.2 Rationale for titanium usage

Weight Savings

The high strength and low density of titanium (~40% lower than that of steel) provide many opportunities for weight savings. The best example of this is its use on the landing gear of the Boeing 777 and 787 aircraft and the Airbus A380. Figure 1.1 shows the landing gear on the 777 aircraft [1-4]. All of the labeled parts are fabricated from Ti-10V-2Fe- 3Al. This alloy is used at a minimum tensile strength of 1,193 MPa; it is used in replacement of a high-strength lowalloy steel, 4340M, which is used at 1,930 MPa. This substitution resulted in a weight savings of over 580 kg. The Boeing 787 used the next-generation high-strength titanium alloy, Ti-5Al- 5V-5Mo-3Cr, which has slightly higher strength and some processing advantages. The use of titanium in landing gear structure should also significantly reduce the landing gear maintenance costs due to its corrosion resistance. The low density and high strength make it very attractive for reciprocating parts, such as connecting rods for automotive applications. Again, the price is too high for family vehicles but the U.S. Department of Energy is investing in a substantial effort to make titanium components for automobiles and trucks affordable. (Titanium is successfully utilized for high-end racing cars, where cost is not that much of an issue.)

Space Limitations

This application does not come up often, but it is an important one. The best example for this is the landing gear beam used on the 737, 747, and 757. This component, running between the wing and fuselage, supports the landing gear. Other Boeing aircraft utilize an aluminum alloy for this application, but for the above aircraft the loading is higher and the aluminum structure will not fit within the envelope of the wing. An aluminum alloy would be the preferred option as it is much lower in cost. Steel would be another option, but that would be higher weight.

Operating Temperature

The structure in the engine and exhaust areas operates at elevated temperature, so the primary options are titanium- or nickel-base alloys; again, the nickel alloys would add significant weight. Titanium engine alloys are used up to about 600 °C. There are applications, such as the plug and nozzle (Figure 1.2), which experience temperatures higher than this for short times during certain operating conditions. The temperature limitation for titanium alloys, other than specialized engine alloys, is about 540 °C. Above this temperature oxygen contamination becomes an issue, embrittling the surface. Titanium is also used at cryogenic temperatures for structures such as impellors for rocket engines.

Corrosion Resistance

Titanium has a very tenacious nascent oxide which forms instantly upon exposure to air. This oxide is the reason for the excellent corrosion resistance. Corrosion is not a factor for titanium in an aerospace environment. Titanium does not pit, which in the author’s opinion is the rationale for the excellent service experience. In service, aluminum and steel alloys will eventually form corrosion pits, which serve as stress risers which will then initiate stress corrosion or fatigue cracks. This does not happen with titanium. This corrosion resistance carries through to the chemical, petrochemical, pulp, paper, and architectural industries. Titanium and its alloys have excellent resistance under most oxidizing, neutral, and inhibited reducing conditions. It is also corrosion resistant within the human body. Biocompatibility is also excellent; it is used for prosthetic devices and bone will grow into properly designed titanium structures. Commercially pure titanium is also being used for exterior architectural applications, a practice started in Japan. It is used for exterior surfaces as it will never require any maintenance. The most famous of these is its use on the exterior of the Guggenheim Art Museum in Bilbao, Spain.

Composites Compatibility

Titanium is compatible with the graphite fibers in the polymeric composites. There is high galvanic potential between aluminum and graphite, and if the aluminum comes into contact with the graphite in the presence of moisture the aluminum would be corroded away. It can be isolated from the composite by methods such as a layer of fiberglass, but in areas that are difficult to inspect and difficult to replace, titanium is used as a conservative approach. In addition, the coefficient of thermal expansion (CTE) of titanium, while higher than that of graphite, is much lower than that of aluminum. Even in the operating temperature range of fuselage structure, about – 60 °C at cruise to + 55 °C on a hot day, the difference in CTE using aluminum structure attached to the composite would result in very high loading. This is not an issue with titanium structure. Obviously, the longer the component, the bigger the issue would be for utilizing aluminum.

Low Modulus

The primary area where this is important is in the replacement of steel springs. With the modulus being about half that of steel, only half the number of coils are required. That in conjunction with the high strength and density being about 60 % of that of steel could ideally result in a weight savings of about 70 % of that of a steel spring. In addition, the titanium offers much superior corrosion resistance, reducing maintenance costs.

Armor

Titanium has excellent ballistic resistance and provides a 15–35 % weight savings when compared to steel or aluminum armor for the same ballistic protection at areal densities of interest, which has resulted in substantial weight savings on military ground combat vehicles. Lighter vehicles have better transportability and maneuverability. The excellent corrosion resistance, low ferromagnetism, and compatibility with composites also provide significant benefits. Two programs that use titanium in upgraded vehicles are the Bradley Infantry Fighting Vehicle (Figure 1.3) and Abrams Main Battle Tank.[2] The relatively high cost of titanium has been successfully mitigated by using plate produced from electronbeam, cold hearth, single melt ingot.

1.1.3 Unique attributes of titanium

General corrosion resistance has already been discussed. With regard to stress-corrosion cracking (SCC), commercially pure and most titanium alloys are virtually immune unless there is a fresh, sharp crack in the presence of stress. If the titanium is cracked in air, the protective oxide will immediately re-form, and SCC may not occur. If the crack is initiated in sea water, for instance, then SCC could occur on certain high-strength alloys or high oxygen grades of commercially pure titanium. Even here, the SCC may be mitigated if the part is not loaded immediately. Dawson and Pelloux[4] showed that fatigue crack growth of Ti-6Al-6V-2Sn can be reduced when tested at a low frequency as long as the stress intensity is below that of the stress corrosion threshold. This is attributed to re-passivation (re-formation of the oxide) in the sea water at the lower frequency whereas there is insufficient time for this to occur at higher frequencies.

The modulus of ß-alloys can be altered significantly. Ti-15V-3Cr-3Al-3Sn with 60 % cold work had a tensile strength of ~1,070 MPa with a modulus of ~76–83 GPa. When aged at 480 °C the strength and modulus were ~1,515 MPa and 103 GPa, respectively. Titanium alloys containing Nb, Zr, and Ta, referred to as gum metal, developed for the medical industry, have elastic moduli as low as 40–50 GPa depending on orientation and processing. These moduli are close to that of bone, making it ideal for prosthetic applications. Cold work decreases the modulus while increasing the strength [5].

The crystallographic texture of the hexagonal close-packed (HCP) a-phase can have a very significant effect on properties in different directions. Larson6 modeled the modulus of a single crystal of commercially pure titanium and determined that when stressed along the basal pole the modulus is ~144 GPa, but when stressed orthogonal to the basal pole it is ~ 96 GPa. Differences in ultimate tensile strength, which are also an indicator of crystallographic texture, between the longitudinal and transverse direction of about 205 MPa have recently been observed for rolled strip, with continuous rolling in one direction which can result in a strong texture.

The Bauschinger effect, while not necessarily unique, seems to have a stronger effect in titanium alloys than other alloy systems. It is attributed to the limited number of slip systems in hexagonal close-packed (HCP) low temperature α-phase. If a tensile specimen is pulled in tension and the test is stopped prior to failure, and a compression specimen is taken from the gage length of the tensile specimen, a significant drop in the yield strength is observed. A tensile strain of 0.5 % at room temperature can reduce the compression yield by 30 %. This is attributed to the dislocations in the material going in the reverse direction following the same slip path, meaning dislocation barriers do not have to be overcome in the early stages of deformation. The same phenomenon is observed if one strains a compression specimen and then pulls a tensile from its gage length. This effect can be eliminated or mitigated by forming at elevated temperature, or subsequent annealing. Consequently, at least in the aerospace industry, when a titanium part is formed, it is subsequently annealed to avoid this large yield reduction. It does not affect ultimate tensile strength.

Solid metal embrittlement has been a problem with titanium and its alloys, with the most prominent example being cadmium. Intimate contact (forcing the titanium into the cadmium or vice-versa) and high tensile stresses are required for this to occur.

1.1.4. High cost of titanium

As many are aware, the primary factor limiting more extensive use of titanium is its cost. With a significantly higher cost than aluminum and steel alloys, titanium utilization must be justified for each application. There are several factors contributing to this. High energy is required for separation of the metal from the ore. Ingot melting is also energy intensive; in addition its high reactivity requires melting in an inert atmosphere using a water-cooled copper retort or hearth, depending on the melting technique. Machining is also very high cost, on the order of 10–100 times slower than the machining of aluminum alloys. It was recently pointed out by Froes[7] that a kilogram of aluminum sheet could be purchased for a lower cost than that of a kilogram of titanium sponge, the starting material. This sponge still must be multiple-melted with a master alloy addition, forged or forged and rolled to a size appropriate for sheet bar, put into a pack with multiple sheet bars, rolled to the appropriated thickness and etched and ground to the final thickness to obtain the titanium sheet.

With these factors in mind, much of the research and development at Boeing and other original equipment manufactuers and fabricators is being devoted to a reduction of the buy-to-fly ratio of titanium components. For instance, a 40 kg plate may be used to machine out a 5 kg part, meaning almost 90 % of the titanium is turned into chips (scrap). Reduction of that buy-to-fly ratio then means one is procuring a reduced weight of a very expensive material, and also reducing the amount of machining being done on that material. Several technologies are being pursued to accomplish this. These include welding, greater use of extrusions where appropriate, superplastic forming and superplastic forming with diffusion bonding, hot stretch forming to obtain more precise formed shapes, and even powder metallurgy. With regard to welding, both fusion and solid-state welding are being investigated. An example of the buy-to-fly reduction which can be achieved via laser welding is illustrated in Figure 1.4. Electron beam and friction stir and linear friction welding are also being studied. Alloys with improved machinability are also being pursued.

1.2 Friction and wear

1.2.1 The Importance of Testing in Tribology

Friction and wear are caused by complicated and multiplex sets of microscopic interactions between surfaces that are in mechanical contact and slide against each other. These interactions are the result of the materials, the geometrical and topographical characteristics of the surfaces, and the overall conditions under which the surfaces are made to slide against each other, e.g., loading, temperature, atmosphere, type of contact, etc. All mechanical, physical, chemical, and geometrical aspects of the surface contact and of the surrounding atmosphere affect the *surface* interactions and thereby also the tribological characteristics of the system. Therefore, friction and wear are not simply materials parameters available in handbooks; they are unique characteristics of the tribological system in which they are measured.

For most surfaces in relative sliding or rolling contact, the area of real contact is much smaller than the nominal contact area. The applied load is carried by a number of small local asperities making up the area of real contact, and the friction and wear behavior results from the interactions between these local contact asperities. At the regions of these local contacts, the conditions are characterized by very high pressures and shear stresses, often well above the yield stress of the materials, high local (flash) temperatures of short duration, and maybe also very high degrees of deformation and high shear rates. Under such conditions, the local mechanical properties of the materials may be very different from what is found, for example, in normal tensile testing. The importance of oxide layers, small amounts of contaminants, local phase transformations, etc., is also much greater than in large-scale mechanical testing. Consequently, the properties of a material in the real contact areas may be far from those measured in normal mechanical testing procedures, and the coupling between wear and friction properties and traditional mechanical properties, such as elastic modulus and yield strength, is weak. See Zum Gahr (1987) and Hutchings (1992).

It also follows from the systems aspect of friction and wear (and the insight into how complicated a surface contact consisting of interacting local asperities, rather than of flats, really may be) that modeling of friction and wear becomes very difficult. Unfortunately, there are very few reliably and reasonably comprehensive models describing the wear or friction processes. This dearth of good models strongly complicates the interpretation of measured wear and friction data. There is also generally no simple correlation between wear and friction; for example, low friction does not automatically imply low wear rates. See Czichos (1987).

Still, the effect of system parameters on tribological properties should not be exaggerated. Many materials do produce low friction or high wear resistance in most practical situations, and may therefore very well be referred to as low-friction materials or wear-resistant materials. Diamond or Teflon® (PTFE) produce low friction in most sliding systems, but exceptions can certainly be found. Cemented carbides are wear-resistant materials, but they may wear very quickly in corrosive environments. But, because of the system nature of tribological parameters, tabulated friction or wear values for these or any other materials are only meaningful if test conditions are very carefully documented. Conclusively, because tribological properties are not materials but system parameters, tribotesting has to be an integral part of both the process of developing tribomaterials and in the selection of materials for applications involving friction and wear.

1.2.2. Wear or Surface Damage

According to DIN 50 320, or similarly in other terminology standards, wear is the progressive removal of material from a surface in sliding or rolling contact against a countersurface. As described in many textbooks, e.g., Zum Gahr (1987) and Hutchings (1992), different types of wear may be separated by referring to the basic material removal mechanisms, the wear mechanisms, that cause the wear on a microscopic level. There are many attempts to classify wear by wear mechanisms, but a commonly accepted first order classification distinguishes between adhesive wear, abrasive wear, wear caused by surface fatigue, and wear due to tribochemical reactions. Over a longer sliding distance, either one mechanism alone, or a combination of several of these wear mechanisms, causes a continuous removal of material from the mating surfaces, and thereby also adds to the friction force that opposes the sliding. Such continuous, steady-state wear and friction conditions may be quantified in terms of wear rates, i.e., removed material mass or volume per sliding distance or time, or its inverse, the wear resistance, and in terms of friction forces or friction coefficients.

However, not all types of tribological failures are due to wear in the sense of a continuous material removal from tribosurfaces, and the tribological properties of the materials in a component are not always best described by their wear resistances or friction properties. Instead a broader study of the various types of surface damages that occur may be more meaningful.

If for example the lubrication of a piston-cylinder system fails, the result will generally be an increased temperature leading to softening or even melting of the surface asperities, followed by an increasing adhesion, material transfer, and local surface welds between the piston and cylinder surfaces; the engine seizes, as exemplified in Figure 1.1. Or, taking cutting tools as another example, the reason for lost cutting performance may very well not be a continuous wear of the cutting edges. Instead a few sudden, catastrophic and discrete events, such as grain pull-outs, edge fractures, or sudden local overheating causing plastic deformation, may lead to lost edge geometry followed by reduced tolerances, unacceptable surface finish, or increased cutting forces. In both these examples the actual wear rate may be very low and perhaps of no importance for the occurrence of the seizure or the lost cutting edge performance; but still, the effect of the events on the performance of the tribosystems is dramatic.

Often, the wear process will undergo several stages as sliding proceeds; at least three stages are commonly identified: The wear starts with what could be called a run-in stage, during which steady-state conditions are building up (Figure 1.2). The running-in may be very important for some sliding systems, as for many types of bearings and gears. During this stage the mating surfaces conform to each other in such a way that the load is more favorably distributed over the surfaces.

During the early running-in stages, the wear rates may be relatively high; running-in should, however, be short compared to the whole lifetime of the component. Steady-state conditions with low wear rates and stable friction values should prevail for most of the lifetime of the system, but low steady-state wear rates will eventually alter clearances or surface properties to the extent that components fail, during a brief, final, catastrophic stage during which wear rates are high and severe surface damage occurs.

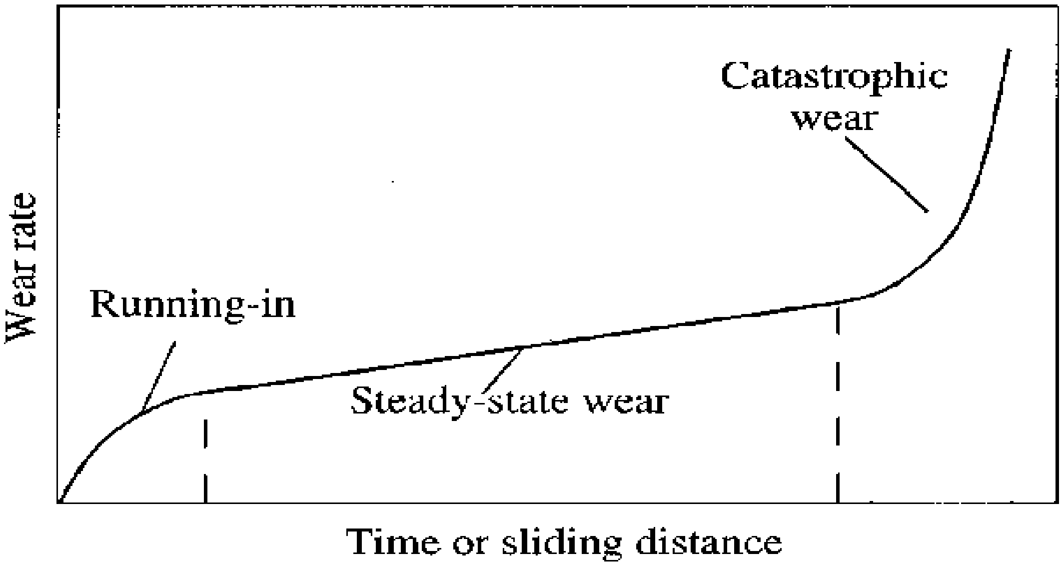


Figure 1.1 - Typical wear stages appearing over longer service times in sliding contacts

Figure 1.2 - Eized piston from combustion engine

The variety of surface damage types that may occur is vast. An attempt to provide some organization of all the possible types of surface damages is found in Hogmark et al. (1992). The following classes of surface damage of tribological importance are there described (Figure 1.3):

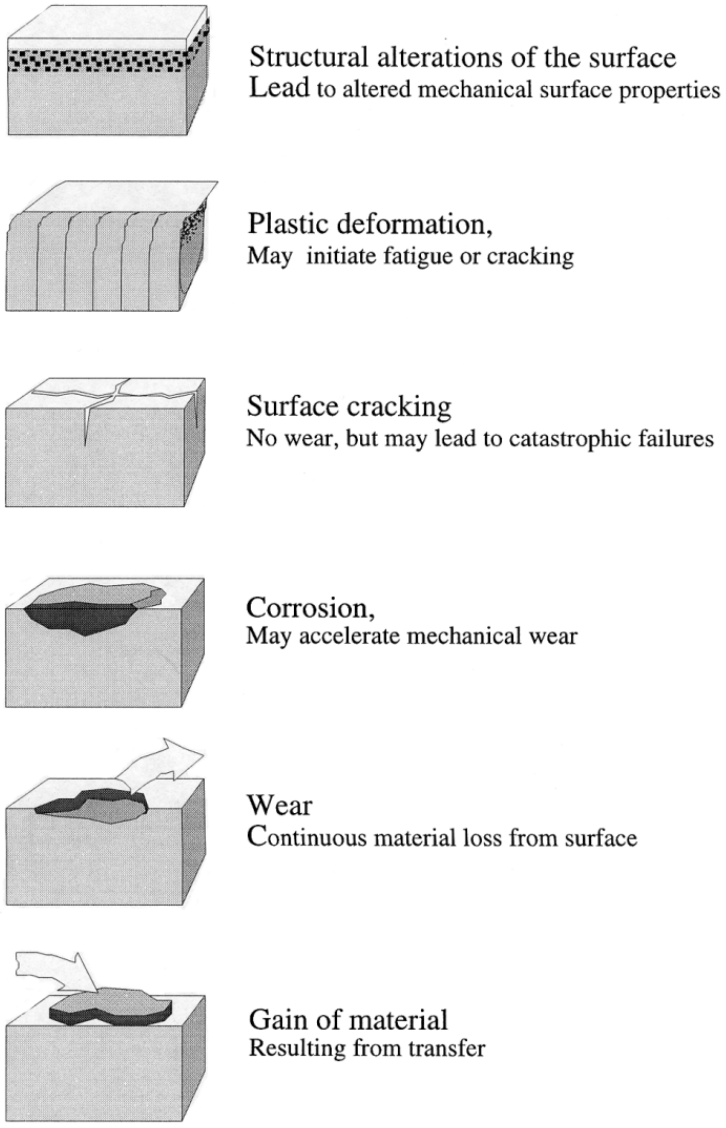


Figure 1.3 - Classification of surface damages and wear

Only wear rates or friction forces measured during the stable, steady-state conditions are useful in characterizing the long-term properties of the system. Damages to a failed component, which occurred just shortly before the failure, are not characteristic of the continuous wear of the materials, and can therefore not explain the series of events leading to failure. Identifying the stage during which a compo- nent's surface damages (or their precursors) did appear, and what their importance is to overall perfor- mance of the component, is one of the more difficult parts of analyzing the failure of tribological components, and probably also the point at which many analyses go wrong. To predict the onset of severe wear regimes is a challenge [4].

- Structural changes of the surface, for example phase transformations, formation of diffusion zones or recrystallization. Such surface changes may occur solely because of mechanical deformation of the surface, or be the result of heat generation causing diffusion or chemical reactions. Structural surface changes do not necessarily imply wear, but they may alter the mechanical properties of the outer surface layers and may constitute the initial stages of wear or other types of failures.
- Plastic deformation caused by mechanical stresses or by thermal gradients at the surface. Although plastic deformation of surface asperities or of an entire surface zone does not necessarily need to be associated with gradual wear, it is of the utmost importance in the creation of any surface damage that may eventually lead to catastrophic failures.
- Cracking in the surface zone may also be caused by exaggerated surface stresses, fatiguing cyclic deformations, or of repeated thermal alterations. Cracking may also be an initial mechanism that eventually leads to large-scale damage without causing any progressive wear during the service stage.
- Corrosion or other chemical attacks may represent the main wear mechanism, but more frequently they assist in mechanical wear processes. Frequently, chemical attacks are the cause of lost surface finish and accelerated crack propagation.
- Wear or surface damage involving continuous material loss due to various types of microscopic material removal mechanisms, causing material to leave the surface as debris. The wear mecha- nisms may ultimately be both mechanical and chemical.
- Gain of material, such as material transfer from the countersurface, resulting from excessive heating of the surfaces, agglomeration of debris such as may appear in seizure, or embedment during erosion. The resulting “third-body” layers are typical of conformal sliding contacts.

Very commonly, the damage observed on a tribologically loaded surface is a result of two or more coexisting or interacting surface damage types. Interacting damage types may lead to unproportionally high wear rates, as for example in oxidation-enhanced surface cracking; adhesive wear may however also be suppressed by oxidation.

In the selection and design of tribological test systems, and in the choice of test parameters, great care must be taken in considering whether measured wear rates or friction forces are the best characterization parameters for the system. Perhaps the study should focus on the occurring types of surface damage instead. Generally a combination of the two is most rewarding. Likewise, it is important to consider what stages in the life-cycle of a tribosurface a test should evaluate: wear rates or wear mechanisms during steady-state conditions or surface damages responsible for the failure. In many cases microscopy or other surface characterization techniques may be more important than wear rate or friction measurements. As further described below, a selected tribotest always has to reproduce the specific type of wear mechanisms or surface damages that appear in the intended application.

1.2.3 Classification of Tribotests

Tribological tests can be performed in an almost endless number of ways. As the outcome of a tribotest is strongly related not only to the characteristics of the materials couple, but also to the whole mechanical system and its environment, the process of selecting the most appropriate test for a specific purpose is fundamental to making meaningful interpretations; it is crucial to plan tribotesting in detail, as shall be further described below. A rational tribotest classification facilitates the tribotest planning.

It is convenient to classify tribological test methods according to their degree of realism, i.e., how closely they imitate the conditions of a real application. Generally a high degree of realism is aimed for, but there are also many reasons to evaluate materials in tests far from any application. Consider for example the aspects of cost, test time, and the accurate control of test conditions, or the wish to perform a scientific study of individual, isolated wear mechanisms. For such evaluations, clearly the simulation of an application does not have the highest priority.

One of the most accepted ways of classifying tribotests, found for example in the DIN 50 322 German industrial standards or Zum Gahr (1987), identifies five levels of simple tests in addition to the field test of the entire system (Figure 1.4). If for example the wear characteristics of the cylinder–piston system in a car engine are to be investigated, a field test would include the whole vehicle driven under realistic service conditions. The whole vehicle could, however, also be evaluated in a bench test, which to improve the degree of test condition control is performed in a laboratory or other controlled milieu. Serving the purpose of reducing cost, only the important subsystem (which is still a real system and not a model), the engine in this example, may be tested under controlled conditions in a laboratory. To simplify even further, only the important machine components can be evaluated in a component test. Although a well- planned component test might at first seem similar to any bench or field test, the alterations in the system's complicated environments are likely to affect the test conditions significantly; heat dissipation, vibrations, conditions of lubrication, etc., will not be entirely identical. To further increase efficiency and the degree of control over the test conditions, a simplified component test or a full-model test may be explored. With a simple model test a large range of materials can be easily, quickly, and cheaply evaluated, under well-controlled test conditions. The degree of realism, however, in the data and the surface damage features, and also the possibility of making reliable conclusions about performance or usability in an application, decreases when we go from the field test to the simpler model test.

Any model test may be further classified according to the characteristics of the tribosystem, as illustrated in Figure 1.4. This classification originates from the frequent wish to evaluate new materials or new designs for one or two components in already existing machinery. Because of cost and time schedules, the evaluations should be performed in some kind of simplistic test equipment; the components are real, but the rest of the tribosystem has to be simulated.

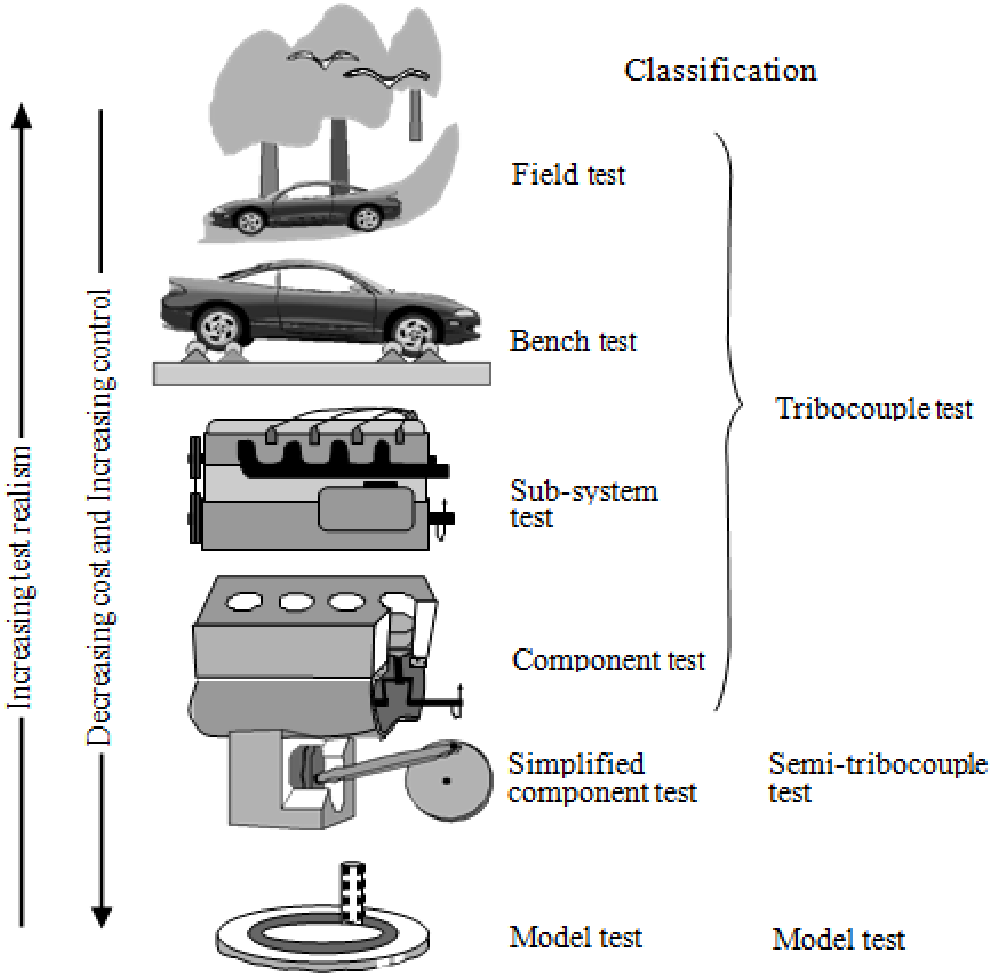


Figure 1.4 - Classification of tribotests according to the degree of realism

In such situations one may distinguish between tests with full tribocouples, thus involving the real components in both of the sliding surfaces, or semi-tribocouple tests in which only one of the surfaces represents an actual component. In a pure model test both tribosurfaces are replaced by simulated components.

In addition, tribotests may be classified as open or closed, with respect to the type of tribological contact situation. If one tribosurface continuously follows the same track on the counterbody, the system is closed, whereas the sliding track is continuously renewed in an open system. (Open or closed may also refer to systems with fresh or recycled particles or oil.) One can also distinguish between tests involving unidirectional or reciprocal sliding, or specify whether the contact involves impacts. Sometimes it may be convenient to distinguish between conformal or nonconformal (alternatively counterformal) contacts. For counterformal geometries, the contact area changes (often increases) as wear proceeds, leading to varied contact conditions, as for example, when a sphere is worn against a flat. Further test configurations are outlined in a later section on selected examples of tribotests.

1.2.4 Tribotest Planning

It follows from the systems aspect of wear and friction, i.e., the insight that tribological properties depend on the whole tribosystem and not merely on the materials, that any tribological testing should be preceded by a thorough evaluation of the characteristics of the system to be evaluated and the purposes of the test; a tribotest should always be designed to meet a defined need.

Reasons to perform a tribotest:

- Ranking of materials for existing equipments
- Selections of materials for new applications
- General, application independent, characterisation of wear and friction properties of materials
- Studies of wear mechanisms appearing in selected tribological applications

One such need to perform a tribotest may be to rank a set of materials in terms of their friction and wear properties in a certain, well- defined system, either with the purpose of selecting a material for an existing piece of machinery, which the tribotest then should imitate, or to select a tribological material for a construction under development, for which field tests or component tests are impossible.

Alternatively, the purpose of tribotesting may be to increase the fundamental and general understanding of how a material behaves in tribological applications. For that purpose, the response of that material to each individual type of wear mechanism has to be studied; this includes the exposure of the material to a variety of model tests simulating different mechanisms under systematically varied loading conditions. For each mechanism, the materials are characterized in terms of wear resistance, friction properties and typical types of surface damage — what may be called the tribological profile of the material. This is the scientific procedure to evaluate the tribological properties of new materials, and the purpose may be to recommend tribological applications for a new material.

In evaluating materials for specific applications, the tribotest selection procedure becomes critical. Always choose the highest possible level of realism in the tests (i.e., higher test level according to Figure 1.4), considering the aspects of time, cost, and test condition control. As the degree of realism in the test increases, the interpretation of the test results becomes more reliable and can be more safely applied to the application in mind. A lower test level ranking means that more care must be taken to ensure that the friction and wear mechanisms of the service component are indeed simulated in the test, and surface damage analysis thereby becomes an important part of the tribotesting procedure. Also in terms of test parameters, the closest possible resemblance to the application should be aimed for. Imitate the loading situation, the contact pressures, sliding speeds, contact frequencies, ambient temperatures, atmospheres, lubricants, etc. (Hogmark et al., 1991).

Consequently, the first step in the tribotest planning process is to study the application carefully in order to simulate the loading conditions as closely as possible. Secondly, the appearing wear mechanisms, specific for the service conditions have to be identified, and as a third step, a tribotest may be selected, possibly following an iterative process of wear mechanism control.

The most basic and important criterion for ensuring the relevance of a model test is the close reproduction of the wear mechanisms appearing in the application during service conditions. The imitation of the actual wear mechanism is decisive for the friction and wear behavior of the tested materials. The wear mechanism, or set of wear mechanisms that a tested material is exposed to, are determined by the properties of the counterface material together with all test parameters. Temperature in particular may greatly influence wear behavior, even if the mechanism itself is under control. Main- taining the proper temperature may be difficult even if all other conditions are satisfactory, e.g., because the test pieces may be smaller than the actual components, providing a smaller heat capacity, or because heat dissipation from the tribocontact or cooling rates through the atmosphere or lubricant might differ.

Very often laboratory model tests are deliberately designed to increase, or accelerate, the wear rate of a test in order to speed up the evaluation. This is most generally achieved by exaggerating either contact pressure or sliding speed, or both. Unfortunately, test acceleration by exaggerating the contact pressure and sliding speed often alters the wear type, particularly through changing the temperature conditions, and accelerated tests that do not reproduce the true wear mechanisms are of limited value. For wear types that result from a large number of microevents, the obvious example being erosion by hard particles, the test procedure can be accelerated by increasing the rate at which the events appear, for example by increasing the rate of erodent hits, or the density of grit in an abrasive type of wear. For simulation of tribosystems with intermittent contact, a decrease in the duration of the noncontact phase may be a good way of accelerating a test [5].

Another, often neglected part of tribotesting, also emerging from the system aspect of tribological properties, is the importance of using reference materials. Strictly seen, tribological properties are only comparative parameters, and even in a tribosystem as well characterized as it realistically can be, a wear rate or friction value measured for a sole material shall be used with skepticism. The selection of reference materials may follow different routes. In the ranking procedure for existing machineries, of course materials commonly used in the application are adequate references, but in a general tribological eval- uation of an uncharacterized material, reference materials well known for specific behaviors, e.g., ductility, resistance to surface fatigue, low friction, etc., may be selected for comparison purposes. To gain knowl- edge about the wear mechanisms and to facilitate the overall ranking of materials, it may even pay to include materials which are known to behave poorly in the application.

1.2.5 Evaluation of Wear Processes

The most commonly used techniques to evaluate wear are weighing and measurement of changes in dimensions. Weighing may often be difficult if the worn volumes are small compared to the weight of the component, as is further discussed in the later section on mild wear. The wear may also be unevenly distributed over a surface, making the measurement of local wear damage more relevant than the total mass loss. Laboratory model tests may allow a continuous recording of the wear, whereas this may be more problematic in the evaluation of actual components, for which estimations of wear scar dimensions with microscopy is more realistic.

The identification of wear mechanisms and surface damages is an important part of any tribotesting procedure and should accompany the measuring of wear and friction values. Therefore, the study of worn surfaces, for example with microscopy or surface topography techniques, becomes an integral part of the evaluation procedure. When examining a worn surface it is important to be attentive to the type of surface damage which sets the life time of the component; this may not be the most spectacular feature appearing on the wear scar. In other words, the identification of the most important mechanisms of a wear process is an important part of the evaluation process.

Advices for the evaluation of wear:

- Identify what the life-limiting surface damage is and specify its location
- Study functionable, not yet fauled, components and compare to unworn surfaces
- Make cross-sections for deeper information
- Study also the countersurface and the wear debris

For large components, the use of replica techniques may prove fruitful. This identification procedure may be very difficult and there are no universal procedures to follow.

Be attentive to what has caused the failure and identify the location of the damage on the surface. Consider whether the failure is the result of continuous wear, or of suddenly appearing damage. Also be aware that a worn out or failed detail seldom gives information about the wear mechanism which caused the wear during service, since these may be hidden by damage that occurred during the end phase of the failure. Study components that have not yet failed, and compare worn and unworn components. This helps to differentiate between surface features which appeared during the manufacturing, and those caused by the service conditions.

Study the worn surface in cross-section. This provides information about the depth of the damage, crystallographic changes caused by temperature; the lack of surface zones may indicate chemical wear.

Study the countersurface. This may provide further hints about the wear process, such as transferred layers of material or embedded hard particles. Try to collect wear debris; its size, shape, and chemical content may provide ideas about wear mechanisms and surface temperatures.

Because of the number of parameters influencing friction and wear, and their potential fluctuations and time dependence, scatter of data is one of the prime problems in tribotesting. The influence of both systematic and random deviations has to be taken into account. The causes of scatter may be found far from the materials or the tribometer itself; surface preparations, heat treatments, variations between batches, humidity variations, etc., may all strongly affect the measured values of friction and wear. Therefore the number of tests required to achieve a reliable result is a matter of constant debate among tribologists. It is no understatement that the result of a single measurement should be considered with great prudence. To minimize the number of influencing parameters, it is generally favorable if all tests in an evaluation procedure can be run by the same operator during a limited time period.

1.2.6 Tribotests - Selected Examples

Large amounts of test equipment for the evaluation of wear and friction properties, often referred to as tribometers, have been designed over the years for a variety of purposes. In this context, only a small number of model tests will be presented; these tests merit particular attention either because of being frequently used, or for representing interesting recent developments in the field of tribotesting. In addition to model tests, a large number of more application-oriented tests are in use, particularly in the industrial sector. As part of the development of materials for cutting and grinding tools, bearings, seals, etc., accelerated application-close trial tests are frequently used. For further examples of tribotests, see Blau (1992) and Normung (1986). The tribotest examples below are organized according to the main wear mechanism they are designed to simulate.

1.2.7 Abrasive Wear

Among the basic wear mechanisms, pure abrasion, which is grooving by hard particles or hard asperities on a countersurface, is probably the most meticulously studied. Compared to other types of wear, the analytical models developed to describe abrasion are much more reliable and comprehensive, which strongly facilitates the interpretation of test results. For well-characterized materials, rough material rankings are sometimes possible without any testing at all. In pure abrasion there is a linearity between wear volume and sliding distance (as long as the wear of the abrasives is negligible), which is in strong contrast to many sliding contact situations. For relatively ductile materials, including most metals, a proportionality between abrasive wear resistance and indentation hardness is also generally observed, although the dependence on hardness is strongly different for different groups of ductile materials. There are also functional analytical models for the effect of grit shape and size, and for the abrasion properties of materials consisting of several phases (see Zum Gahr [1987] and Axén et al. [1996]).

Since the abrasion rate depends very strongly on the shape, size, hardness, and friability of the abrasive particles, the choice of grit is particularly important in the evaluation of abrasion properties. A strong decrease in wear rate occurs when the sample hardness exceeds the grit hardness (Hutchings, 1992). Also, abrasion with loose particles, called three-body abrasion, produces fundamentally different wear types compared to tests with fixed abrasives (two-body abrasion). Three-body abrasion becomes intimately sensitive to the properties, particularly the hardness, of the counterbody. A strong shift in the wear rate has been identified at unity ratio of grit hardness to workpiece hardness. Also the degree of freedom of motion of the grit, the compliance of the support, etc., affect the characteristics of an abrasion test. Thus, also for pure abrasion, materials may behave, and also rank differently depending on the details of the test procedure [6].

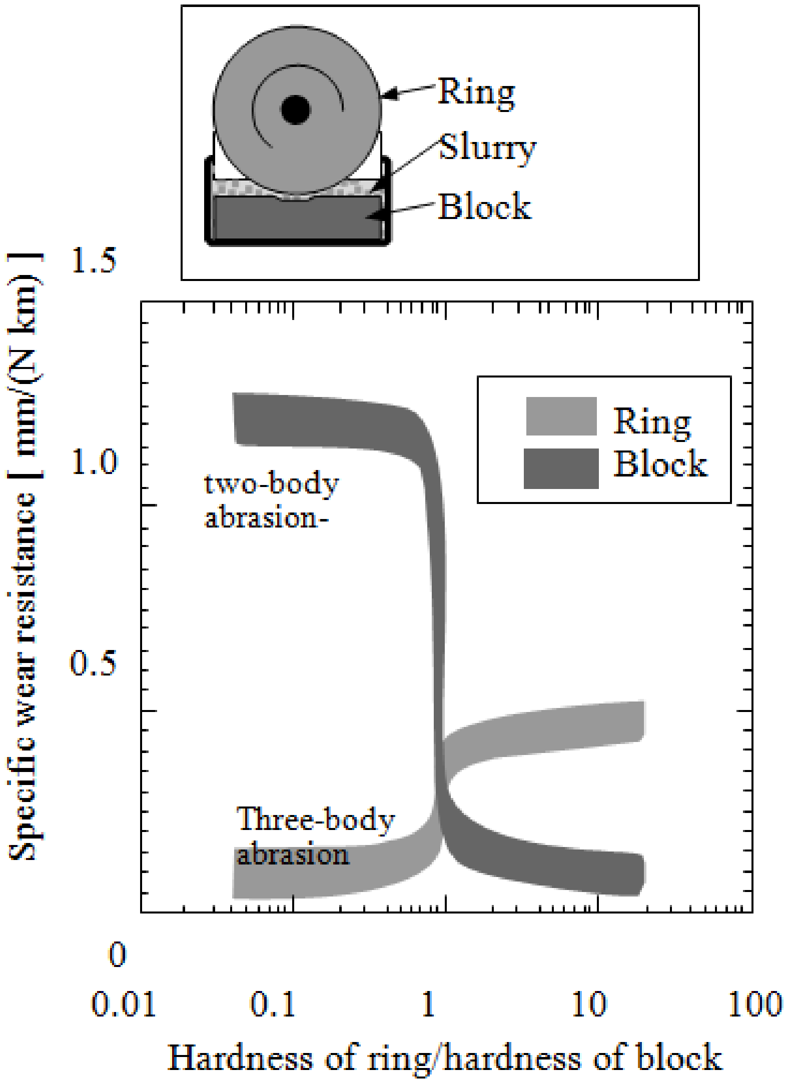
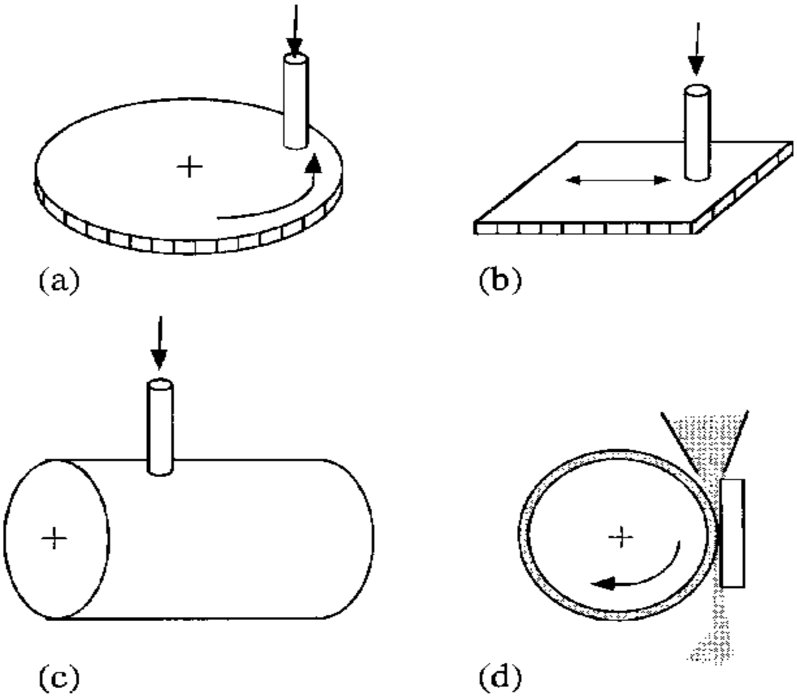


Figure 1.5 - Wear rate as a function of the hardness ratio of the two sliding surfaces in an abrasion test with initially loose particles, evaluating a tool steel and an aluminum alloy heat treated to different hardnesses

Most common tests to evaluate the resistance of materials to abrasive wear explore either wearing surfaces with fixed abrasives, e.g., grinding papers or grinding wheels, or use loose abrasives which are fed into the contact between the sample and a countersurface, for example a rotating wheel or disk. The configuration details for abrasion tests vary widely. The pin-on-disk (a) or pin-on-drum (c) configurations are very common, the latter forming the basis of a tribometer defined in the German Industrial standards in DIN 53516, and being commonly used for polymers. Rectilinear sliding of pins over flats is also in use (Figure 1.6).



a) - pin-on-disk, b) - pin-on- square,
c) - pin-on- cylinder d) - pin-on-drum

Figure 1.6 - Common abrasive wear test configuration

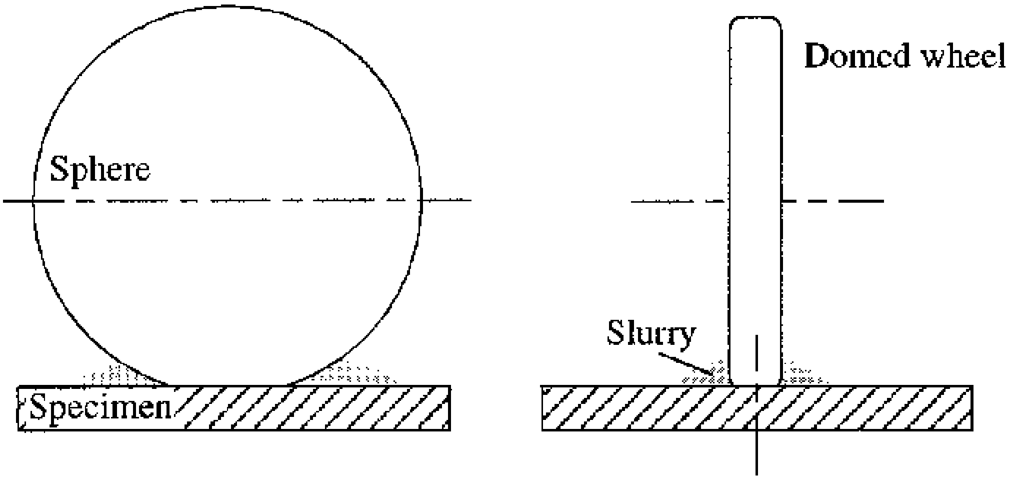


Figure 1.7 - Schematics of common crater grinding tests configurations

Figure 1.8 illustrates the frequently applied rubber wheel abrasion test, defined in the U.S. standard ASTM G65. The specimen, in the form of a block is pressed with a constant load against a rotating wheel, the rim of which is covered with a thick layer of replaceable rubber. In tests with fixed particles, the wear rate decreases with the number of passes over the same track due to the degradation of the abrasives. Therefore many apparatuses move the test pins along spiral tracks to make them meet constantly fresh abrasives. The three-body tests avoid this problem to some degree, but becomes more sensitive to the properties of the counterbody providing the grit support. Also more application-close abrasion tests have been developed. One example is the laboratory scale jaw- crusher, used to simulate the gouging abrasion which occurs in mining operations. This test has been adopted to the U.S. standard and is described in ASTM G81.

In contrast to these fairly coarse abrasion tests, the recent development of a finer type of abrasion test, often referred to as the dimple grinder test or the ball crater test, has attracted much attention. With the help of a rotating wheel or ball, small craters, often less than 1 mm in diameter and with depths of less than 10 microns, are ground on the sample surfaces using grit slurries (Fig. 13.10). The tests have proved very practical because of their simplicity of operation, the good control of test conditions, the simplicity of measuring the wear volumes, and because of the fact that the small wear scars make the tests virtually nondestructive. Crater grinding tests have been evaluated on hard coatings, ceramics and metals bulks, thin amorphous metal bands, small ceramic crystallites, and on soft coatings of paint, in most cases with very promising results (Kassman et al., 1991 or Rutherford et al., 1996).

A test procedure to evaluate the abrasion properties of multiphase materials consisting of hard phases in a softer matrix is outlined in Axén et al. (1996). This procedure has found industrial use for the evaluation of the wear resistances of the hardphase in grinding tools and multiphase materials with superhard reinforcements used in the machining and drilling of rock.

The work is based on the concept of load distribution between the phases in a multiphase material, and it clarifies how the load applied to the sliding surfaces may be shared between the different phases of a multiphase material. Generally, a more wear-resistant phase takes a higher load and thereby contributes more to the wear and friction properties of the composite material, as described in detail in Axén et al. (1996). The wear resistant phase may also carry low load shares and contribute very little to the wear resistance of a multiphase material. By identifying the upper and lower limits for how well a hard phase can carry load, the possible load distribution limits, and thereby the optimal and minimal wear resistance of a composite, can be predicted. In practice, measured values of the wear resistance and friction of the individual phases, or extrapolated values measured for materials with very low or high amounts of reinforcements, are used to calculate upper and lower limits for the wear and friction properties of the multiphase material [7].

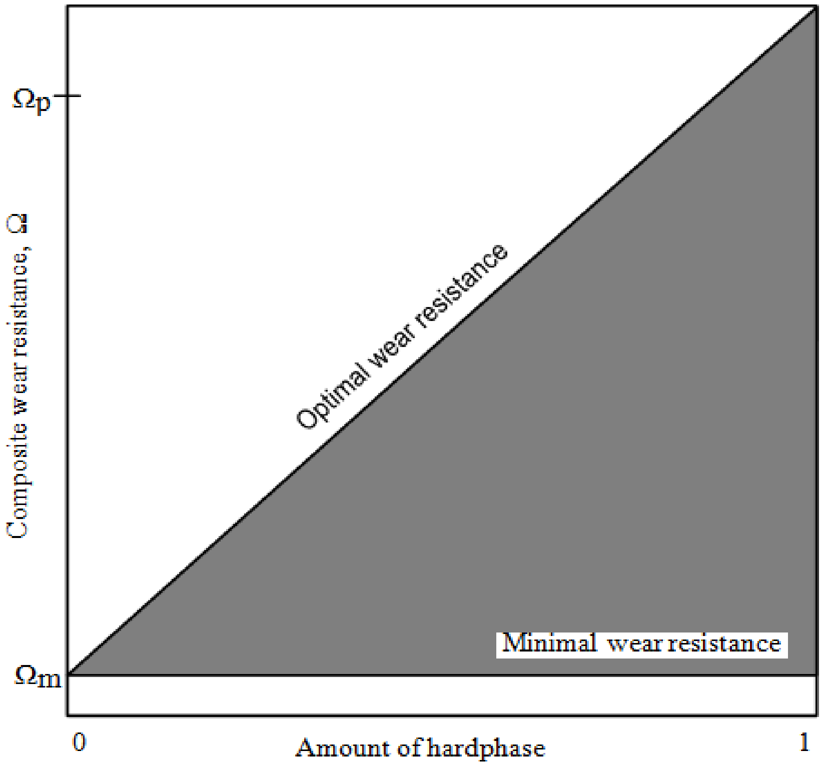


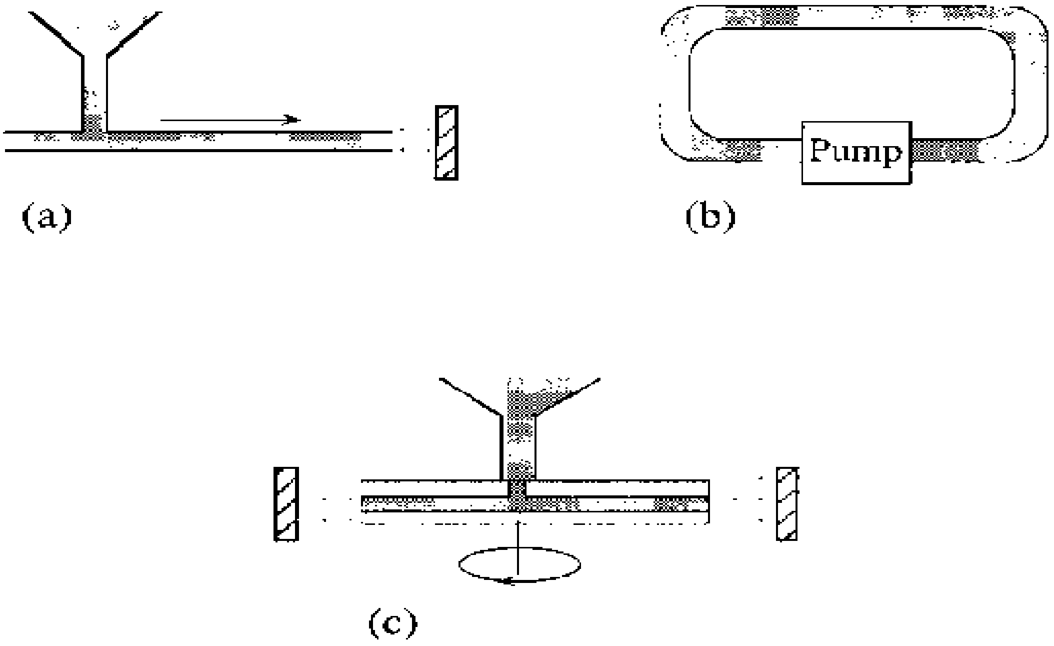
Figure 1.8 - Load-specific composite wear resistance as a function of the amount of reinforcement

The contribution of hard reinforcing phases to the properties of the composite is thereafter quantified in terms of load distribution coefficients relating to the possible maximum or minimum values. The procedure is practical in the evaluation of reinforcements because it is based rather on measurable values of load distributions between the phases, and is less dependent on the subjective study of wear mechanisms (Figure 1.9).

In the context of abrasion tests, which are basically multiple-tip grooving tests, single-tip scratch tests also merit being mentioned. Equipment to slide a diamond stylus over the sample surface under con- trolled loading and speed conditions is commercially available and commonly used to evaluate both bulk materials and coatings. Often hardness indentors of the Rockwell C or Vickers types are slid over the sample surface to produce a controlled groove along which failure mechanisms can be studied with microscopy, or by the use of acoustic emission detection units and friction recordings (Axén et al., 1997).

1.2.8 Erosive Wear

Solid particle erosion is the wear caused by hard particles bombarding a surface. Like abrasion, erosive wear can involve both plastic deformation and brittle fracture, and the details of the appearing wear mechanism depends on both the wearing material, the erodents, and the condition of the impacts, primarily particle mass, velocity, and impingement angle. The erosion behavior of materials is closely linked to the properties of the eroding grit; shape, hardness, toughness, and size all strongly affect the erosion rate of any test material. Deterioration of the erodents during testing has to be taken into account, and testing with recycled particles should be avoided, unless appropriate for the application being investigated.



a) - single-line, b) – round, c) - bi-linearly

Figure 1.9 - Basic test configurations for erosive wear

The erosion rate increases with the speed of the eroding particles and their mass and tends to fall with the hardness of the wearing material, although the hardness dependence may be weak for certain groups of materials (Söderberg et al., 1981).

The effect of impact angle is fundamentally different for materials of different mechanical properties. The erosion rates of brittle materials generally increase continuously with impact angle, from the particles streaming close to parallel to the surfaces, to the case of orthogonal impacts. Ductile materials, however, tend to erode the fastest at an intermediate impact angle, often at around 20 to 30 ° measured from the eroded surface tangent (Kosel, 1992; Hutchings, 1992).

Erosion properties thus also depend on the details of the test configuration, and there is a need to control test conditions accurately. Test methods for laboratory evaluation of erosion can be classified according to the principles for the propulsion of the eroding particles toward the samples. Most commonly the particles are carried either by a fast gas or liquid stream exiting through a nozzle directed toward the test materials; alternatively they are propelled by the rotary motion of a disk or propeller. Figure shows different types of testing methods. In the jet impingement or gas-blast method illustrated in Figure, particles are accelerated toward the sample by a stream of gas or fluid along a nozzle. Gas- blasting methods are standardized in the ASTM G76 and the DIN 50332 industrial standards. Systems exploring a loop through which gas-born particles or slurries are pumped are used to establish wear properties of pipework components pneumatic or hydraulic components.

The centrifugal techniques, illustrated, or rigs based on whirling arms have the advantage of allowing accurate calculation of particle speeds; in the gas or liquid carrier methods, particle speed has to be measured by separate systems. Centrifugal techniques also facilitate the evaluation of large numbers of samples in each test run. Also there is detonation gun equipment for single particle impacts.

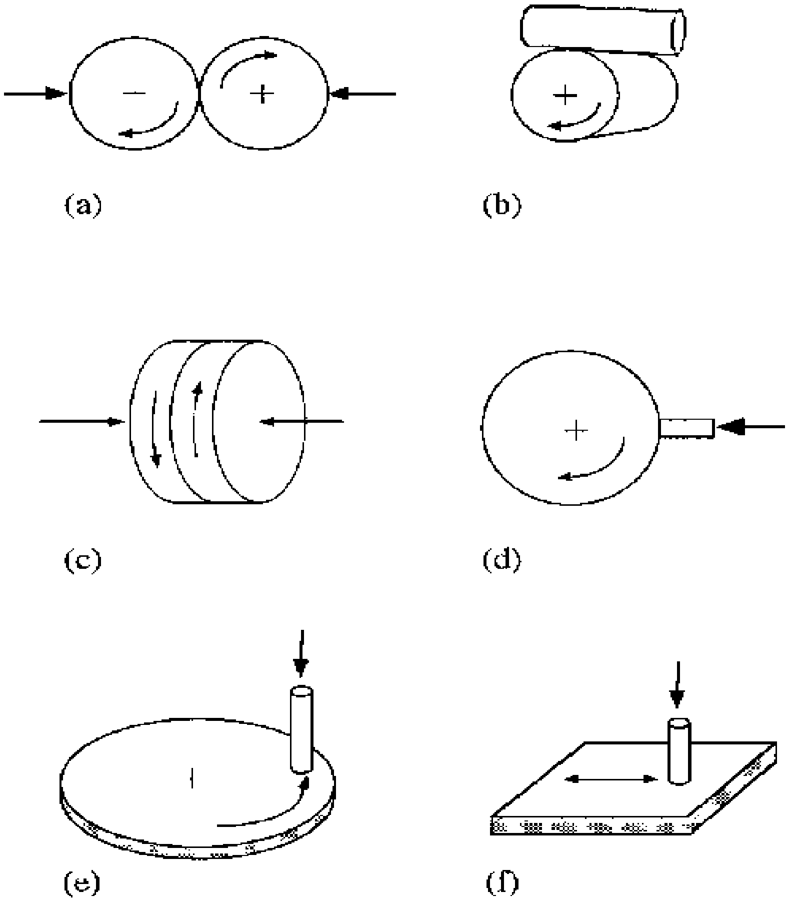
Some attempts have been made to use erosion for the evaluation of the durability of coatings. Thick, thermally sprayed coatings can be tested along the same principles as bulk materials. For thin coatings, Shipway (1995) has developed a procedure capable of extracting the erosion resistance of the coating material from deep wear scars involving simultaneous wear of coating and substrate. The technique is based on assumptions about the variation of particle flux along the radius of the circular wear scars produced by a stream of particles leaving a long parallel nozzle. The radius of the area corresponding to the exposed substrate, or the start of the coating, thereby also indicates the mass of particles required just to remove the coating. By following the rate at which this radius widens with the dose of erodents, values for what Shipway called the “erosion durability” can hence be established. The technique has been shown to be sensitive to the adhesion of the coating to the substrate [8].

1.2.9 Wear in Sliding and Rolling Contacts

Sliding or rolling wear do not specify any wear mechanisms, but refer to the types of contact between two surfaces in relative motion. Instead numerous types of material removal mechanisms may appear in these types of contacts.

Surface damages or wear based on adhesion or on surface fatigue are common, but also grooving by surface asperities, i.e., abrasion, tribochemical wear types and other mechanisms are possible. Nevertheless, wear and friction in sliding and rolling contacts are naturally of great interest because of their common occurrence in many machine elements. Therefore, numerous tests for sliding and rolling wear evaluations have been produced.

Because of the vast variety of surface interactions and types of surface damages that may occur in sliding contacts, apparently minor alterations in the test conditions can lead to radical and sharp changes in the dominant wear mechanisms and the associated wear and friction values. When choosing model tests for materials ranking, it therefore becomes important to simulate the conditions of the application in detail. Contact stress, thermal conditions, sliding speed, and chemical environment are all vital test parameters in sliding and rolling wear.



a) - spheres, b) - cylinders, c) - planes, d) - face slip, e) - peripheral slip, f) - reverse slip

Figure 1.10 - Illustrations of common sliding wear test configuration.

The interpretation of sliding wear test results is generally much more difficult than for abrasion or erosion. While these types of wear by hard particles are the result of a very large number of microevents, a sliding contact may initiate a variety of interacting phenomena whose character changes as the test proceeds. As a consequence, wear rate is often not proportional to the sliding distance, and correlations to any bulk materials properties, such as hardness, toughness, etc., cannot generally be taken for granted. Sliding wear tests may be performed with a large variety of geometrical configurations (Figure 1.10).

It is practical to distinguish between tests where the test bodies are symmetrically or asymmetrically arranged. Figure illustrate symmetrical versions for which self-mated materials should ideally give identical results. Symmetrical arrangements are not often used in model tests; an example, however, are rings arranged as in Figure 1.10 (f) simulating the symmetrical and conformal contact of axial seals.

Asymmetrical configurations, exemplified in Figure are more common, and because of the noncontinuity of the contact, they produce different results depending on the positioning of the test sample. Probably because of their simplicity and flexibility in terms of test conditions and specimen shape, rigs of the asymmetrical pin-on-disk configuration have become some of the most popular model tests for evaluating sliding wear. Pin-on-disk rigs with attached heat stages and cover boxes enabling tests in controlled atmospheres are commercially available. Also pin- or block-on-cylinder configurations are frequently used. The configuration of a stationary pin loaded against a sliding block, or vice versa, primarily finds use for friction measurements in monopass tests.

Very important for all these configurations is to make the distinction between conformal and nonconformal (counterformal) contacts. The contact may ini- tially be of the point or line type, and then continuously grow as wear proceeds, or the contact may from the start be extended over a large area which remains constant as the test proceeds, as illus- trated.

Several sliding wear test configurations are specified in national standards. Tests based on the block-on-ring (ASTM G77), crossed cylinders (ASTM G83), pin-on-disk (ASTM G99), and sphere- on-disk (DIN 50 324) are examples of American and German industrial standards. However, standardizations in tribology only serve the purpose of facilitating comparisons between results from different laboratories; the system aspect of wear and friction is unavoidable, being particularly apparent in sliding wear tests.

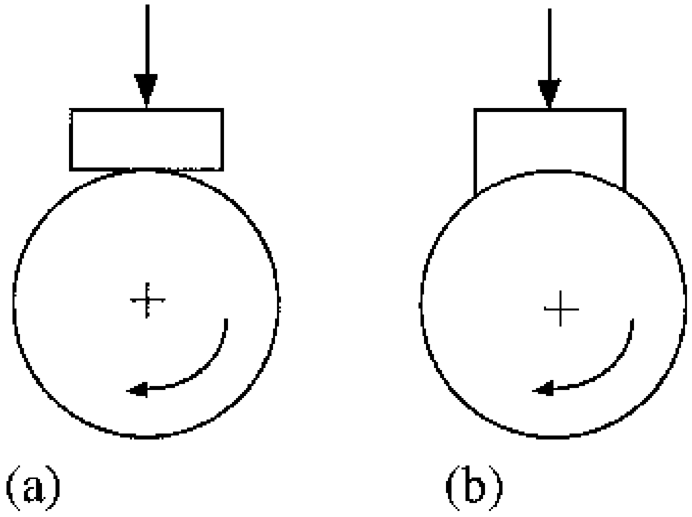


Figure 1.11 - Counterformal (a) and conformal (b) contacts

In one recently developed apparatus to evaluate the sliding behavior of components, the orientation of the test specimens and their motion during testing is arranged in such a way that the contact spot on each specimen moves along a contact path during testing (Jacobson, 1998). In the test two specimens are loaded against each other to form a well defined contact spot on each specimen. The primary novelty of this technique is that, during testing, each contact spot on both specimens only makes contact to one specific spot on the other specimen, and vice versa. The test configuration is typically that of two crossed test bars, cylinders, or similar geometries. During testing the point of con- tact between the bars is for both bars moving from one end to the other.

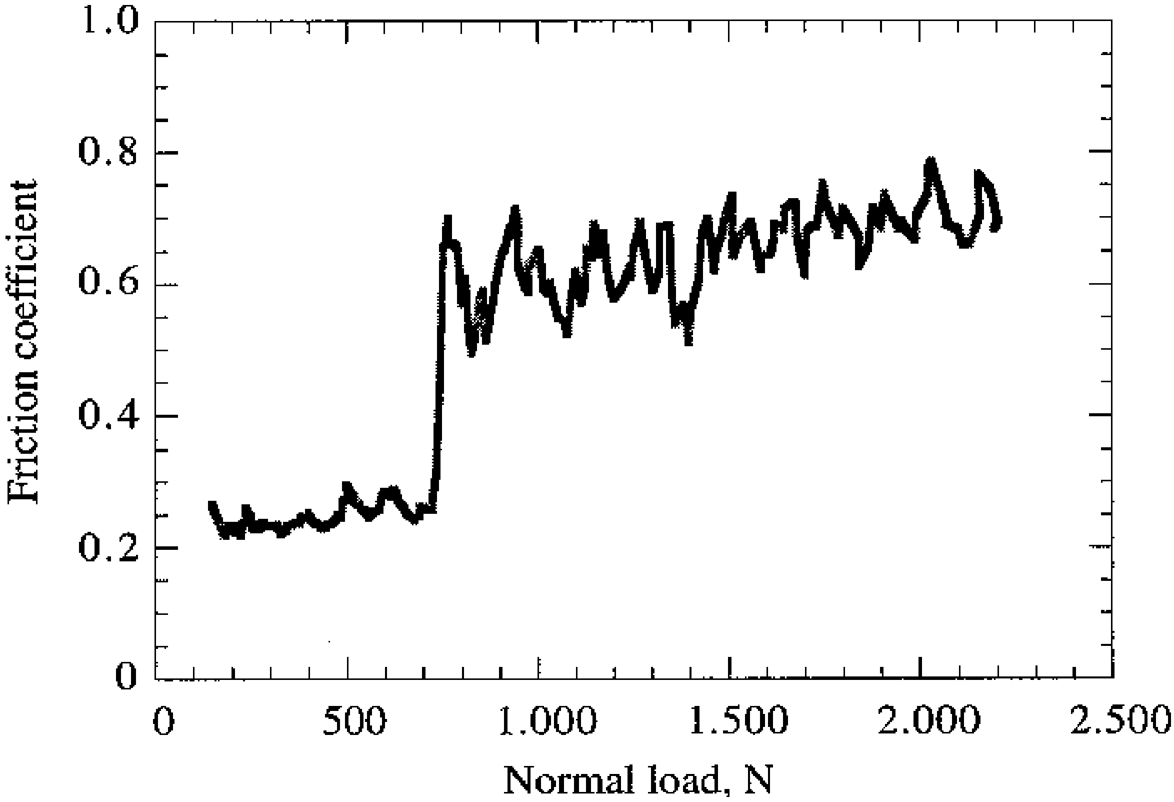


Figure 1.12 - Typical friction graph obtained for a metal in the equipment The friction shows a sudden increase at the load of seizure

Testing is either performed as a single stroke operation or by reciprocally sliding the specimens across each other under controlled loading conditions. The load can be kept constant or increased gradually or stepwise. Indepen- dently of the loading, each point along the contact path of both test rods will only experience a unique load, both if the test is performed as a single stroke or reciprocally.

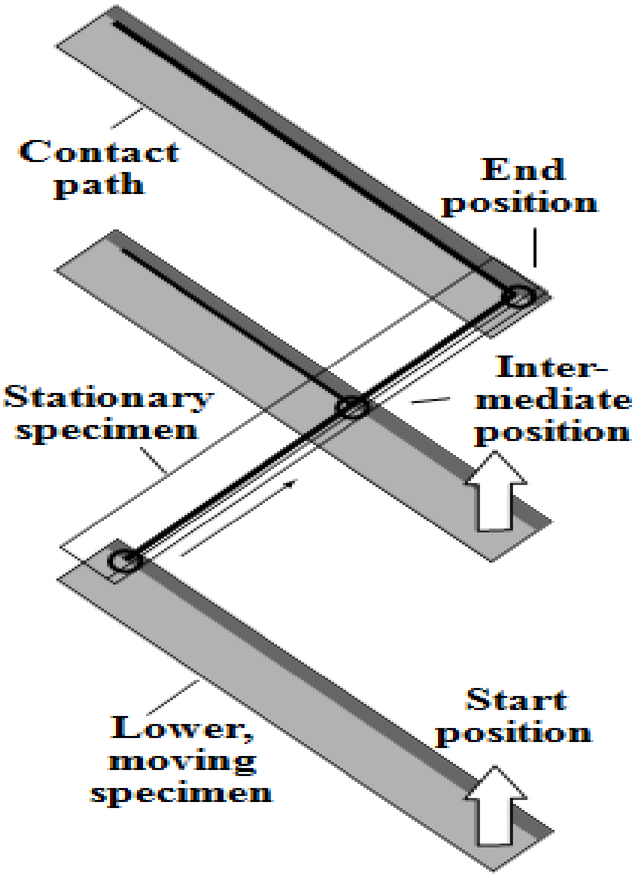


Figure 1.13 - Schematics of equip- ment loading and sliding two test rods against each other. The contact spot path resulting form the movement of the lower specimen moves along the contact path (full black line) on both specimens

1.10 Very Mild Wear

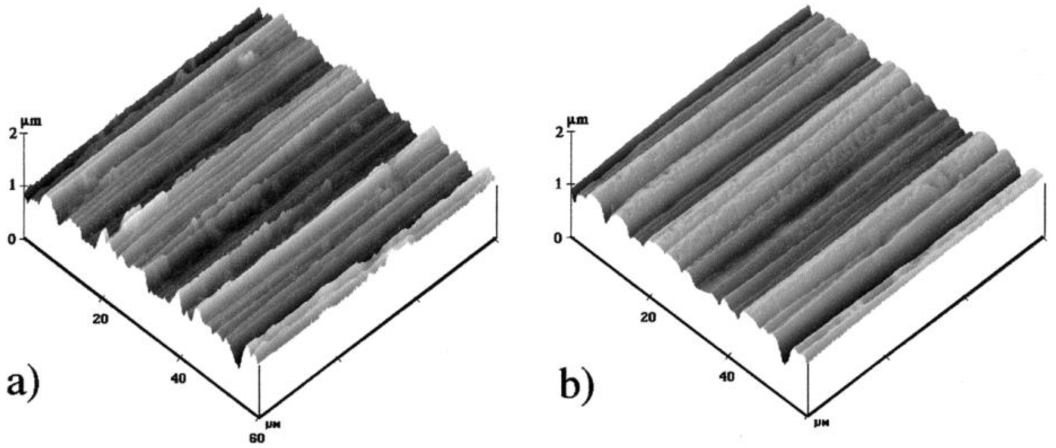
In situations of mild wear, such as the wear of most tribological components involving lubricated sliding or rolling contact, the mass loss is often very small in relation to the total mass of the worn component. For many machine elements it can be assumed that the wear appears on an atomistic scale. A precision balance typically has a resolution of 10^{-6} of the maximum load (e.g., 0.1 mg resolution at 100 g load), which naturally sets a limit to the minimum load possible to quantify in relation to the total weight of the component. Often this excludes the weighing of components before and after wear testing as a method of quantifying wear. Further, weighing gives no information about the distribution of the wear over the worn surface. In most cases this is a serious disadvantage, since the service life is often limited by the maximum wear at some critical location, rather than by the total wear. For further information, Ruff (1992) has given an overview of wear measurement techniques [9-10].

As discussed above, acceleration of the wear situation may lead to changes of the wear mechanisms, and so provide unreliable results, and tests involving normal wear rates may require unrealistically long test times. In such situations modern topographical methods may be the best way to evaluate the wear. With the introduction of high-resolution instruments such as the atomic force microscope (AFM) and optical interferometry, techniques capable of determining height differences in the subnanometer range (with lateral resolutions of about 1 nm and 1 μm, respectively) and storing the obtained topographical data digitally, it is now possible to measure the volume of topographical features in the sub μm range. (The mass of 1 μm^3 of steel equals ca. 10^{-11} g) Another benefit of this kind of instrument is that the topographical data are used directly to render images of the surface, including shading and color-coded heights.

Recently a new method to map and quantify wear was presented by Gåhlin and Jacobson (1998). They used the technique, called the topographical difference method, to evaluate the very minute initial wear of a hydraulic motor cam roller (Gåhlin et al., 1998).

The topographical difference method for evaluation of wear comprises two techniques: topographic image subtraction for wear distribution mapping, and bearing volume subtraction for local wear volume determination. Topographical image subtraction is suitable mainly for qualitative presentation of the distribution of wear over the surface and to indicate the magnitude of the individual wear events. This information is obtained by taking the topographical image of a worn surface and subtracting the previ- ously recorded unworn (or less worn) topographical image of the same surface. This procedure effectively eliminates all unaltered surface features, leaving corresponding areas flat, and exhibits lost material as elevations over this flat surface and gained (plastically displaced) material as depressions. To get a good mapping, the lateral matching of the two images has to be very precise. On the other hand, the technique does not require a height reference, but only the existence of unaltered parts of the surface that become flat after subtraction and thus indicate the “zero wear” level.

Bearing volume subtraction is used to quantitatively determine the volume loss over the local studied area. This is achieved by using bearing histograms to calculate the volume of material left above a common fixed surface level (Figure 1.13). The more the surfaces are worn, the less material is left above this reference level. To obtain the bearing volumes from the topographical data, each measured point (surface element) of the specified surface area is multiplied by its height over the reference level. The accumulated wear volume is then calculated by subtracting this bearing volume by the corresponding volume obtained after the wear test. In contrast to topographical image subtraction, bearing volume subtraction involves no point-to-point comparison and thus does not depend on a precise lateral matching of the two images. The first application of this method to actual components involved wear evaluation of a hydraulic motor.



a) - Initial and b) - worn 2165 h

Figure 1.14 - Topography and corresponding bearing histograms of a chromium steel roller before and after sliding against silicon nitride in a full-scale hydraulic motor test. The average wear depth is about 40 nm, corre- sponding to a mass loss of 10^{-9} g. (10× larger magnification in the height direction.)

The wear of the cam rollers was successfully mapped and measured (Figure 1.14), using a standalone-type AFM. For this application typical average wear depths of 30 nm were registered after a sliding distance of about 15 km (2165 h test time), corresponding to a total wear of about 1 mg of the 600 g roller. The wear distribution map revealed that this minute wear was localized at the uppermost parts of the grinding ridges. These results were obtained on rollers, where the curved geometry put extra demands on the experimental technique. This clearly demonstrates that the topo- graphical difference method is not restricted to simplified laboratory tests [11].

1.3 Fretting Wear in Lubricated Systems

Fretting wear is surface damage that occurs between two contacting surfaces experiencing cyclic motion (oscillatory tangential displacement) of small amplitude. At the contact areas, lubricant is squeezed out, resulting in metal-to-metal contact. Because the low amplitude motion does not permit the contact area to be relubricated, serious localized wear can occur. This type of wear further promotes two-body abrasion, adhesion and/or fretting fatigue (a form of surface fatigue) wear.

When fretting wear occurs in a corrosive environment, both the rubbing-off of oxide films and the increased abrasiveness of the harder oxidized wear debris tend to greatly accelerate wear. When corrosion activity is distinctly evident, as denoted by the color of the debris particles, the process is referred to as fretting corrosion.

1.3.1 Fretting Wear

Fretting wear is also known as vibrational wear, chafing, fatigue, wear oxidation, friction oxidation, false brinelling, molecular attrition, fretting fatigue and corrosion. Because virtually all machines vibrate, fretting occurs in joints that are bolted, pinned, press-fitted, keyed and riveted; between components that are not intended to move; in oscillating splines, couplings, bearings, clutches, spindles and seals; and in base plates, universal joints and shackles. Fretting has initiated fatigue cracks which often result in fatigue failure in shafts and other highly stressed components.

Fretting wear is a surface-to-surface type of wear and is greatly affected by the displacement amplitude, normal loading, material properties, number of cycles, humidity and lubrication.

1.3.2 Fretting Wear Process

Cyclic motion between contacting surfaces is the essential ingredient in all types of fretting wear. It is a combination process that requires surfaces to be in contact and be exposed to small amplitude oscillations. Depending on the material properties of surfaces, adhesive, two-body abrasion and/or solid particles may produce wear debris. Wear particles detach and become comminuted (crushed) and the wear mechanism changes to three-body abrasion when the work-hardened debris starts removing metal from the surfaces.

Fretting wear occurs as a result of the following sequence of events:

- The applied normal load causes asperities to adhere, and the tangential oscillatory motion shears the asperities and generates wear debris that accumulates.
- The surviving (harder) asperities eventually act on the smooth softer surfaces causing them to undergo plastic deformation, create voids, propagate cracks and shear off sheets of particles which also accumulate in depressed portions of the surfaces.
- Once the particles have accumulated sufficiently to span the gap between the surfaces, abrasion wear occurs and the wear zone spreads laterally.
- As adhesion, delamination and abrasion wear continue, wear debris can no longer be contained in the initial zone and it escapes into surrounding valleys.
- Because the maximum stress is at the center, the geometry becomes curved, micropits form and these coalesce into larger and deeper pits. Finally, depending on the displacement of the tangential motion, worm tracks or even large fissures can be generated in one or both surfaces.

As the surfaces become work-hardened, the rate of abrasion wear decreases. Finally, a constant wear rate occurs, which shows that all the relevant wear modes are working in combination.

1.3.3 Fretting Wear Characteristics

The key factor in fretting wear is a mechanically loaded interface subjected to a small oscillatory motion. The relative motion required to produce damage may be quite small, as low as one micrometer, but more often is around a few thousandths of an inch. The wear coefficient depends on the amplitude of oscillation.

Changes in the normal load generally affect fretting wear. Although equipment users often presume that high normal loads will dampen vibration sufficiently to reduce fretting, the increase in contact area produces more surface interaction which tends to outweigh this effect. Consequently, increasing load or unit pressures tend to generate higher wear rates as Figure 1.13 shows.

Three separate mechanisms cause fretting wear: adhesion, traction fatigue and delamination (two-body abrasion). Metallic transfer may or may not take place. Plastic deformation geometrically changes surfaces and high load-carrying regions are created that have areas measured in square millimeters.

The material corresponding to these load-carrying areas is highly work-hardened and leads to forming a new structural phase. These work-hardened areas are brittle, prone to fracture and fragmentation, and generate metallic wear debris and particles having initial dimensions of around one micrometer.

Although fretting can occur in an inert environment, this type of environment is not normal. Even under full lubrication conditions, mineral-base oils exposed to the atmosphere contain at least 10 percent air, so oxygen is present at all friction couples or wearing interfaces. Wearing surfaces and wear debris commonly show a large amount of oxide, leading to the name “fretting corrosion.”

Another facet of the fretting process is the influence of humidity on the rate of fretting wear. Fretting wear decreases substantially for most friction couples (metals) as the relative humidity increases from zero to 50 percent. Wear under humid conditions is always less severe because the moisture contained in the air provides a type of lubricating film between the surfaces [12].

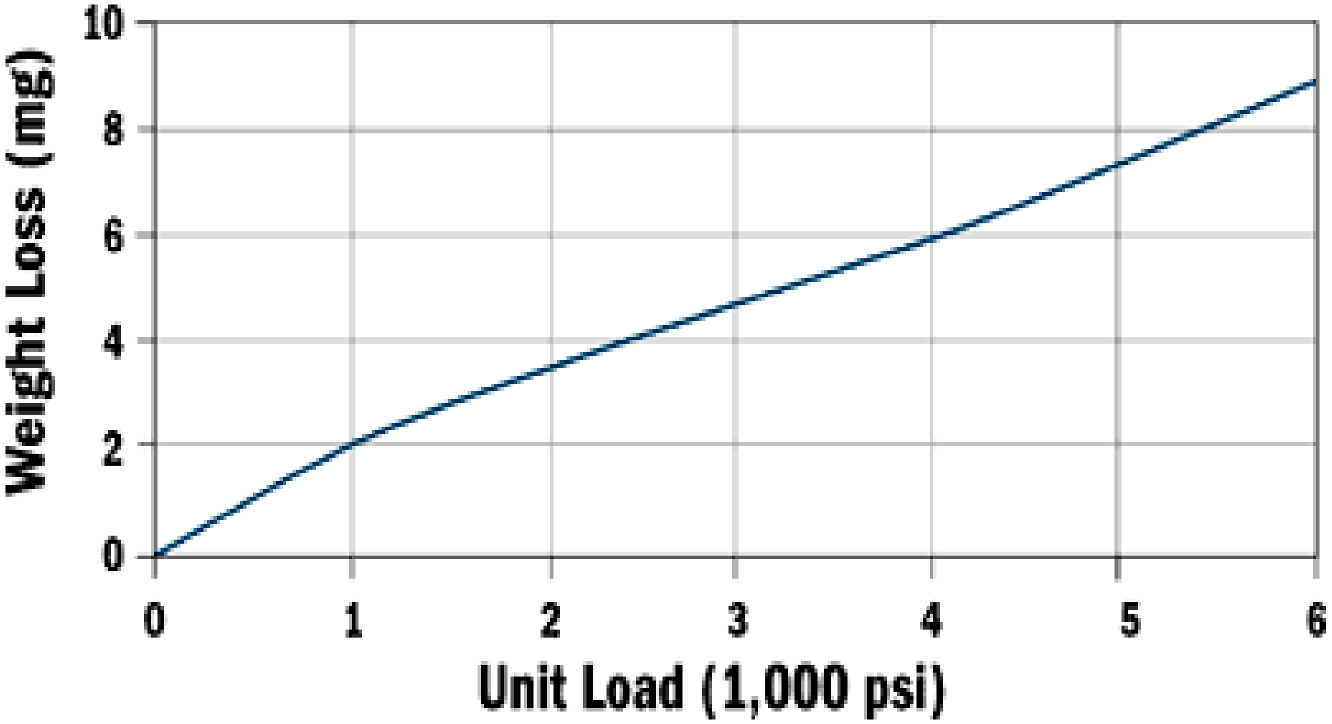


Figure 1.15 - Fretting Wear vs. Normal Unit Load [13]

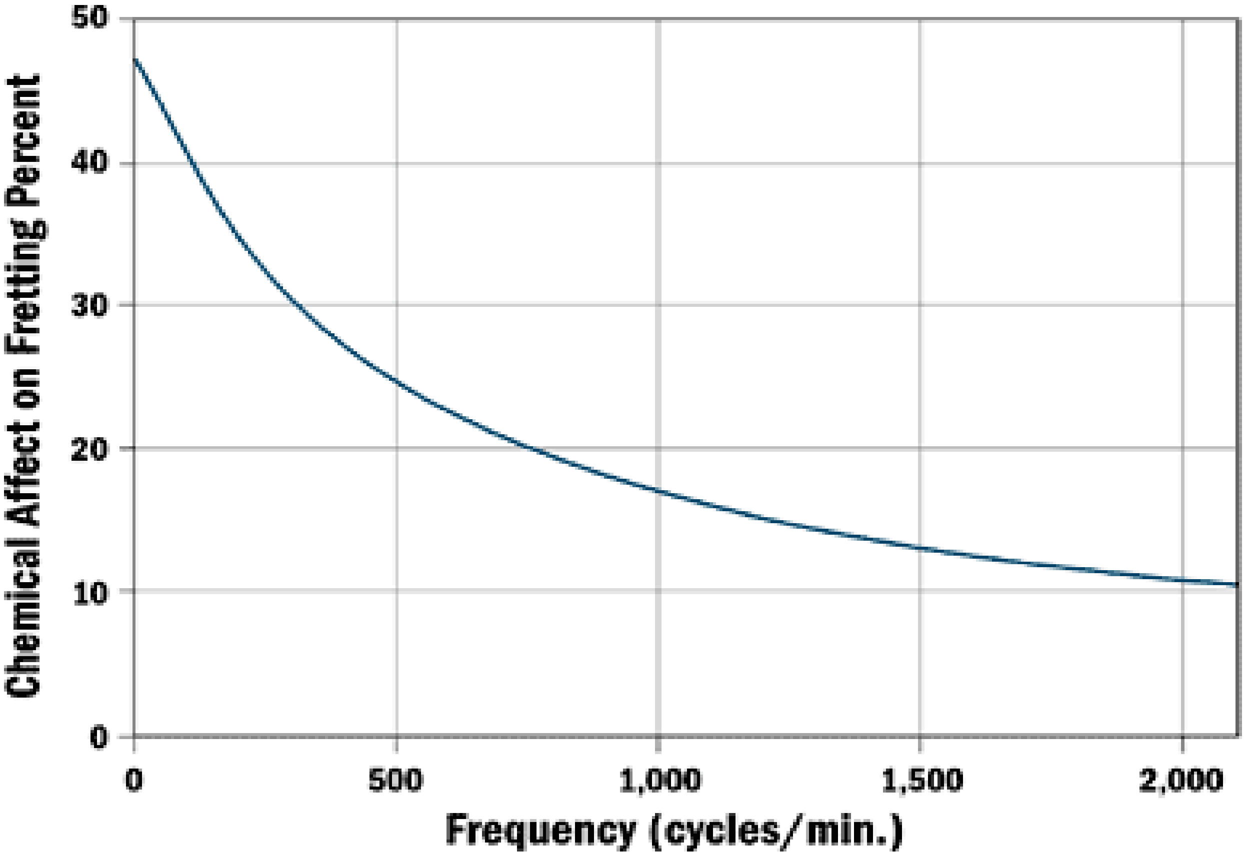


Figure 1.16 - Effect of Frequency on Fretting Damage of Mild Steel

In some cases, moisture allows soft iron hydrates to form instead of the harder, more abrasive Fe_3O_4, magnetite, a magnetic oxide of iron.

1.3.4 Fretting Corrosion

In the past, fretting wear was usually called fretting corrosion because oxidation was supposedly the critical factor causing fretting. In fact, the existence of oxidation products has been a ready means of identifying a fretting process.

Today, engineers realize that fretting occurs in materials that do not oxidize, such as cubic oxide, gold and platinum. Although oxidation does not cause fretting in most common materials, removing wear debris leaves virgin metal exposed to the atmosphere and oxidation usually occurs [14-15].

Strong visual evidence supports the idea that oxide films form and are subsequently scraped away. The metallic surfaces in the fretted region become slightly discolored. The color of wear debris varies with the type of parent material; the corrosion product of aluminum is white but fretting causes it to become black, the corrosion product of steel is gray but fretting causes it to become a reddish brown.

The second aspect that supports this idea is the increase in wear rate. When fretting occurs in an inert environment, the wear rate is considerably less than when conditions cause an oxide film to form and be scraped off.

Because the effect of frequency on wear is amplitude-dependent, two types of fretting wear need to be defined according to the oscillation amplitude. The first type of fretting is fretting corrosion or wear, as previously discussed. The second type of fretting that occurs, in which less material is removed is called fretting fatigue or traction fatigue.

1.3.5 Fretting Fatigue

In fretting fatigue, surface cracks initiate and propagate, thus removing material. The amplitude is small. If the amplitude of slip increases, the fretting fatigue phenomenon can disappear as the wear front begins to advance rapidly enough to remove the initiated cracks before they propagate.

Surface hardness plays a key role in limiting fretting fatigue. If both surfaces are hard, asperities will weld, followed by the shearing of junctions, material transfer and wear particle generation.

If a hard surface is in contact with a soft surface, fretting fatigue wear will likely occur. The harder of the two surfaces creates sufficient traction to cause plastic deformation of the softer surface and particle release through subsurface void nucleation, crack propagation and subsequent loss of surface material. When one surface is much harder and rougher and is driven by less traction force, the asperities will indent into the opposite surface to cause serious abrasion and wire-like wear debris.

1.3.6 Lubricant Influences on Fretting

Fretting seems to progress more rapidly in friction couples that have smooth surface finishes and close fits. Lubricants do not penetrate wear areas with small clearances (described as close fits). In addition, the smooth finish eliminates lubricant-retaining pockets between the asperities in rougher surfaces.

Under these conditions only boundary lubrication condition, the continuous interaction of oil wetted surfaces, can be achieved. Lubricants are not always successful because the reciprocating action squeezes out the lubricant film and does not allow it to be replenished.

Conclusions to part 1

Titanium is an attractive material for numerous industries, but its utilization has been restricted. A broad range of activities are underway to reduce this cost. Significant cost reductions could greatly expand the industrial base. The aviation would like to use it for reduced weight of armored vehicles, the aviation would like to use it for the superstructure of some of its surface ships as they tend to get top heavy, the chemical/petrochemical industry could take greater advantage of its corrosion resistance, and the aerospace industry would use more for weight savings if the price can be driven down. If these industries could be penetrated in a significant way, the industrial base for titanium would expand significantly which should reduce and stabilize the cost. At present, with the only volume users being the chemical and aerospace industries, when the aerospace industry has a significant pickup in orders, such as when the Boeing 787 gets up to production rate, the Boeing requirements will be very high, and the price will go up. This means that some of the industries with a positive but marginal business case may drop their titanium usage. If the price gets to the point where the market can be significantly expanded, the prices should be more stable [16].

Regarding friction and wear, extremely high resolution methods such as the one described above, promise to improve tribological testing of real machine elements by reducing the need for excessively accelerated tests or extremely long test times.

In general, the purpose of the lubricant in most fretting situations is to prevent oxygen from reaching the fretting surface and the wear debris. Liquid lubricants with effective metal deactivator additives can help to reduce the effect of fretting but will not likely stop fretting altogether.

PART 2.

METHODOLOGY OF THE EXPERIMENT CONDUCTION

2.1 Methods of preparing the surface of metal parts before coating

Surface preparation is the essential first stage treatment of a substrate before the application of any coating. The performance of a coating is significantly influenced by itsability to adhere properly to the substrate material. It is generally well established that correct surface preparation is the most important factor affecting the total success ofsurface treatment. The presence of even small amounts of surface contaminants, oil, grease, oxides etc. can physically impair and reduce coating adhesion to the substrate.

Chemical contaminants that are not readily visible, such as chlorides and sulphates, attract moisture through coating systems resulting in premature failure. In summary, theimportance of a chemically clean substrate to provide the best possible contact surface for the applied coating cannot be over-emphasised.

All the technological operations, which the details prior to coating application are exposed to, leave traces on the details surface in the form of pollution. Every product, however it may seem clear at the outer rough inspection, it almost always contains on a surface some pollution, which violates the process of normal coating obtaining.

Contamination on the metal surface may be different in their nature and properties. The most common on the metal surface pollution in their nature are divided into three main types [17]:

- thermal scale, corrosion products, sulfide or oxide films and other chemical compounds;
- fats, ois and other organic matter;
- foreign rigid particles from various sources.

Chemical compounds that are on the parts surface are usually strongly linked with the metal surface. The composition of oxide films is not uniform over the cross section. Usually closer to the boundary metal - oxide are located lower oxides, and at the oxide - the external environment boundary are higher oxides.

For newly manufactured metal products are distinguished two levels of contamination with fats and oils. The surfaces on which a thin layer of mineral oil mixed with dust, grease, and coolant can refer to the first group, the second group includes the surfaces with thick layers of conservation-based lubricants, oils and hard dirt.

The solid particles get onto the surface of metal during polishing and grinding with abrasives, as well as lubricants and coolants at machining. These particles are usually graphite, dust, surface inclusions of mechanically adhering particles of other metals, etc. The developed surface of fine particulate matter causes strong adsorption of the particles among themselves and with the surface details of the formation of stable conglomerates. In addition, solid particles fill cracks, crevices on the surface, blind holes, from where they are most difficult to be removed.

Foreign layer in thousandths of a micron rapidly reduces the adhesion strength of coating with the base metal. With the thickness increase of a foreign layer the adhesion strength of coating to the base metal decreases almost exponentially. The quality of coatings in a great measure depends on the quality of surface cleaning. A long-term verification galvanic coatings defect proves that 70 % of all defects are associated with poor quality of surface preparation before coating [18].

Optimal adhesion to the base material can be achieved if we can add to the crystal structure of the base metal the coating structure in such a way as to form an internal communication in a common crystal structure. To fulfill this condition, preparing to coating application operations is the foundation that determines the quality of details protection.

The choice of a surface cleaning method depends on many factors, primarily on the nature of contamination and cleanliness requirements of the surface. Therefore the choice of treatment method is determined by the type of contamination, material items, the required degree of purification and the cost of the process. All cleaning methods can be divided into two groups [19]:

- methods of pre-treatment;
- methods of vacuum cleaning.

In the first case, the most serious "macroscopic" pollution is removed, i.e. surface irregularities caused by technological processes of manufacture of the samples. The biggest drawback of pre-treatment methods is that in the process of cleaning the surface from some substances, we pollute it with others. For example, the surface skimmed with the solvent is simultaneously contaminated with molecules with dissolved substances contained in the solvent. Acid etching causes physical heterogeneity (after etching the surface remains rough).

Group of vacuum techniques is an essential tool for obtaining a clean surface. These methods are implemented in a high vacuum (10^{-6} Pa and below). Likelihood of re-contamination of the surface in high vacuum is significantly reduced.

Methods for pretreatment of the surface are the following:

- mechanical methods;

This is a blast, abrasive, blasting and brushing treatment, as well as surfaces cleaning in solutions when exposed to ultrasound.

Surface cleaning by hand tools such as scrapers and wirebrushes is relatively ineffective in removing mill scale or adherent rust. Power tools offer a slight improvement over manual methods and these methods can be approximately 30% to 50% effective but are not usually utilised for new steel work fabrications.

- chemical methods;

Steels are mainly etched in acid solutions - sulfuric or hydrochloric. Other etching methods - electrochemical, alkaline, etc. are applied with restrictions. The chemical methods of cleaning include methods for degreasing in various solvents and alkaline solutions.

-plasma methods;

These are new and improved methods of surface cleaning. The metal surface is treated with directional flow of ionized particles (plasma), at temperatures of about 10000 °C. A disadvantage is the complexity and high cost of equipment for the process (including the creation of a special gas environment). At the same time, the methods are versatile and of high performance, and easily combined with the further application of quality coatings.

Vacuum-cleaning of the surface can be realized through the following methods:

- the method of thermal desorption;
- ion etching (ion spray);
- the method for obtaining a clean surface by spraying;
- cleaning method using catalytic reactions;
- the method of cleavage in a vacuum.

The most effective technology for surface preparation of parts, machining of the past, is a chemical pretreatment followed by vacuum cleaning by ion spraying on the surface.

Surface of the metal parts are cleaned from oxides by etching in acid and alkaline solutions. Etching of parts - is the dissolution of oxides in acid or alkali. The choice of correct material depends on the etching properties of metal. Ferrous metals are etched mainly in sulfuric acid or hydrochloric acid [20]. Sulfuric acid - the most common etching agent, because of its cheapness compared with other acids.

Iron oxides Fe_2O_3 and Fe_3O_4 are porly soluble in acid, and etching is mainly due to dissolution of the base metal, followed by loosening of the oxides. If the oxide layer is uneven in thickness, some areas may be over etched. This leads to an increase in surface roughness, which may be unsuitable for coating. To avoid over etching of bases inhibitors are introduced into solution - substances that are adsorbed on the cleaned metal surface to form a film that prevents metal etching. The concentration of sulfuric acid is maintained in the range 150 - 250 kg/m^3, and then the etching rate is maximum. Increasing the etching rate is achieved by increasing the temperature to 40 - 80 ºC.

Oxides dissolve better in hydrochloric acid than in sulfuric acid, so there is less danger of over etching. However, hydrochloric acid can be heated to a temperature not exceeding 40 ºC because of its high volatility and the solutions must often be corrected. For etching hydrochloric acid is used in the same concentrations as sulfuric acid (150 - 250 kg/m^3).

For etching the steels alloyed with nickel, chromium, titanium and other elements, apply a mixture of acids, for example, a mixture of sulfuric, hydrochloric and nitric acid or nitric and hydrofluoric acids. The choice of a mixture depends on the grade of steel, or more precisely the nature of the alloying metals.

2.2 Methods of testing materials and coatings of fretting

The research performance on fretting differs with different methods used, the scheme of loading and type of contact, and in the evaluation of surface damage. The method is chosen according to the two basic requirements [22]:

- imitation of fretting in the laboratory should maximally approach the conditions of this type of surface damage in real structures;
- the selected method should be such that you can compare obtained results with data from other works.

The followings requirements are set to test the devices in connection with the specifics of fretting:

- backlash-free mounting of samples in clamping devices;
- torsional rigidity and low deforming of device;
- availability of vibration skidding movement of controlled frequency and amplitude;
- availability of controlled normal force to create the necessary pressure in contact;
- possibility to supply lubricant or other medium.

The choice of a flat circular contact and swing-rotation movement of contact surfaces is stipulated by the necessity of control of normal load and elimination of edge effect.

The basis of the accepted methods of work contains a comprehensive study of qualitative parameters of friction pares. Scheme of the contact plane-plane type used on installation MFK-1 (ГОСТ 23.211-80), the general view is shown on Figure 2.2.

Figure 2.1 - General view of installation MFK-1 for testing the fretting

The main advantages of this method are:

- quickassessment of durability of materials and coatings under fretting;

- satisfactory reproducibility of test results with a minimum number of test samples;

- simplicity of the method and corresponding equipment;

- possibility of smooth control of the frequency and ampliiude of normal load micro shifts;

- tests using plastic and liquid lubricants;

- registration of friction during testing.

Description of the method is that the rolling cylindrical sample (control sample), adjacent by edge with immovable cylindrical sample at a given pressure is driven to swivel-rotary motion with given amplitude and frequency. Measured wear of stationary sample for a given number of cycles is determined by the value of durability of the investigated material. Plant layout is shown on Figure 2.3.

Installation works as follows: motor 2 transmits rotational motion to eccentric 3 of adjustable eccentricity. Rotational frequency and the number of revolutions are recorded by instrument 1. Eccentric 3 through rod 4 is related to the crank 6 of drive 7 axis 6 of control sample 8swing-rotation motion. Amplitude of control sample 8 displacement and is regulated by an eccentric device 5. Fixed sample 9 is fixed in the centered collet 10 installed on the shaft of the moving stock 11. Samples are loaded by the dynamometer 14 and loading device 15. Size of axial load on the specimens recorded by dynamometer ЗІП 02-79 type ДОСМ-3-0,2(ГОСТ 2283-79) with the boundary measurements from 0.2 to 2 kN. Friction registration is done by deviceНО71.5М *13* through amplifier 8-АНЧ-7М *12* with the help of tenzobeam 11. Number of test cycles has to be controlled by the counter located on the front panel of the aggregate.

Vibration amplitude is governed by the change of eccentric eccentricity (roughly) and by change of the length of the horizontal rod length (exactly). Rough amplitude regulation allows changing its size from 10 to 1000 microns, exact - from 5 to 15 microns. The amplitude of relative displacement is defined as the oscillation difference of movable and fixed samples. Measuring the amplitude is held directly on the samples using an optical binocular microscope МБС-2 (with an increase in from 8 to 56 times) using strobe effect (stroboscope ТСТ-100).

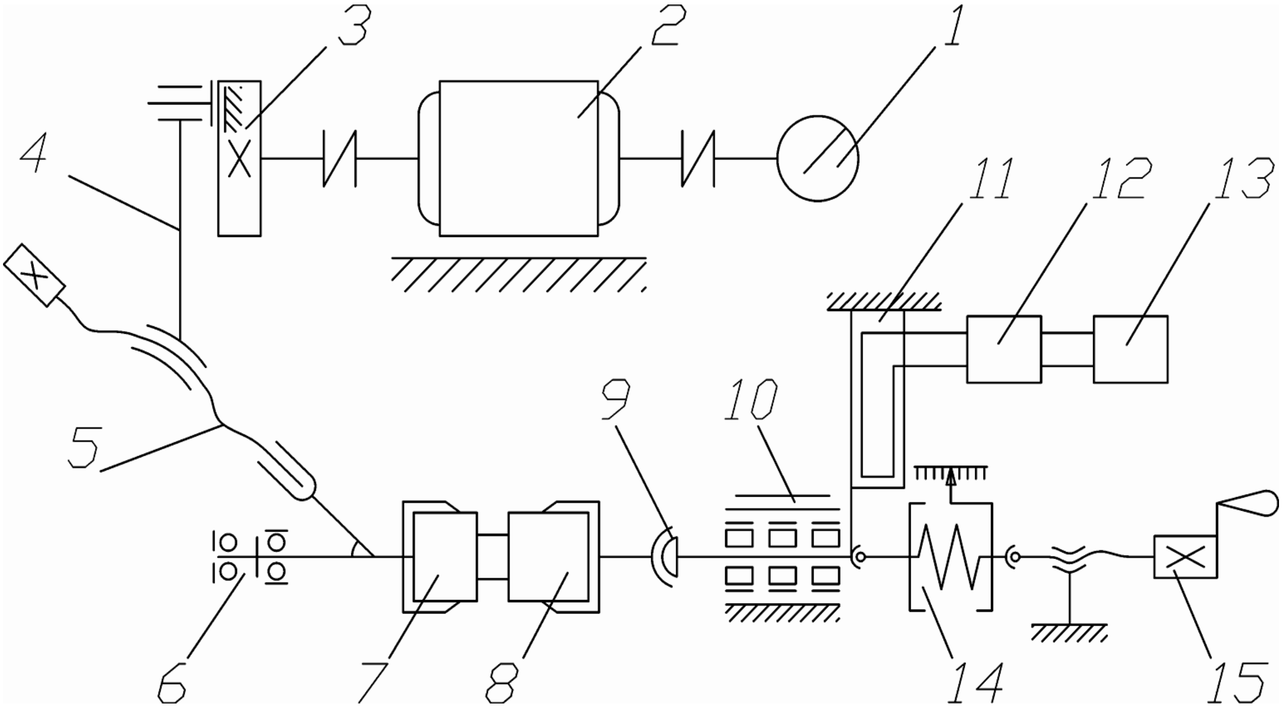
Samples for testing are shown in Fig. 2.4. Contact of test samples is performed on the surface, which is a closed loop with the nominal contact area 0.5 cm^2, 11 mminner diameter and an outer diameter of 13.6 mm.

Samples should be washed and dried before and after the eчperiment. For washing are used liquids: gasoline ГОСТ 443-76, acetone ГОСТ 2603-79, ethyl ГОСТ 18300-72. Before the test the measuring and recording equipment should be checked and marked.

Installation allows testing at next parameters [23]:

- loading of samples in axial direction by 200 - 1000 N;
- swivel-rotary motion of control sample to sample with a frequency of 10 - 30 Hz and amplitude 10 - 1000 microns;

- measuring system settings during testing provides continuous registration of number of cycles of control sample swivel-rotation with an error less than 50 cycles.



1 - revolution counter, 2 - motor, 3 - eeccentric, 4 - vertical rod, 5 - adjusting device, 6 - horizontal rod, 7 - moving sample, 8 - fixed sample; 9 - self orienting collet, 10 - moving stock of 11 – tenzo beam 12 - amplifier, 13 - registering apparatus 14 - dynamometer, 15 - loading device

Figure 2.2 - MFK-1 installation layout:

For the materials testing in liquid environments the special heating chamber is used that provides the possibility of supply and withholding liquid environments in the contact area of the specimens.

The specimens for tests fastened in the unit collets, set in the round openings of chamber, provided with the sealing, manufactured from heat-resistant rubber. The leakage of working environment from a chamber is prevented with a help of sealing regulators.

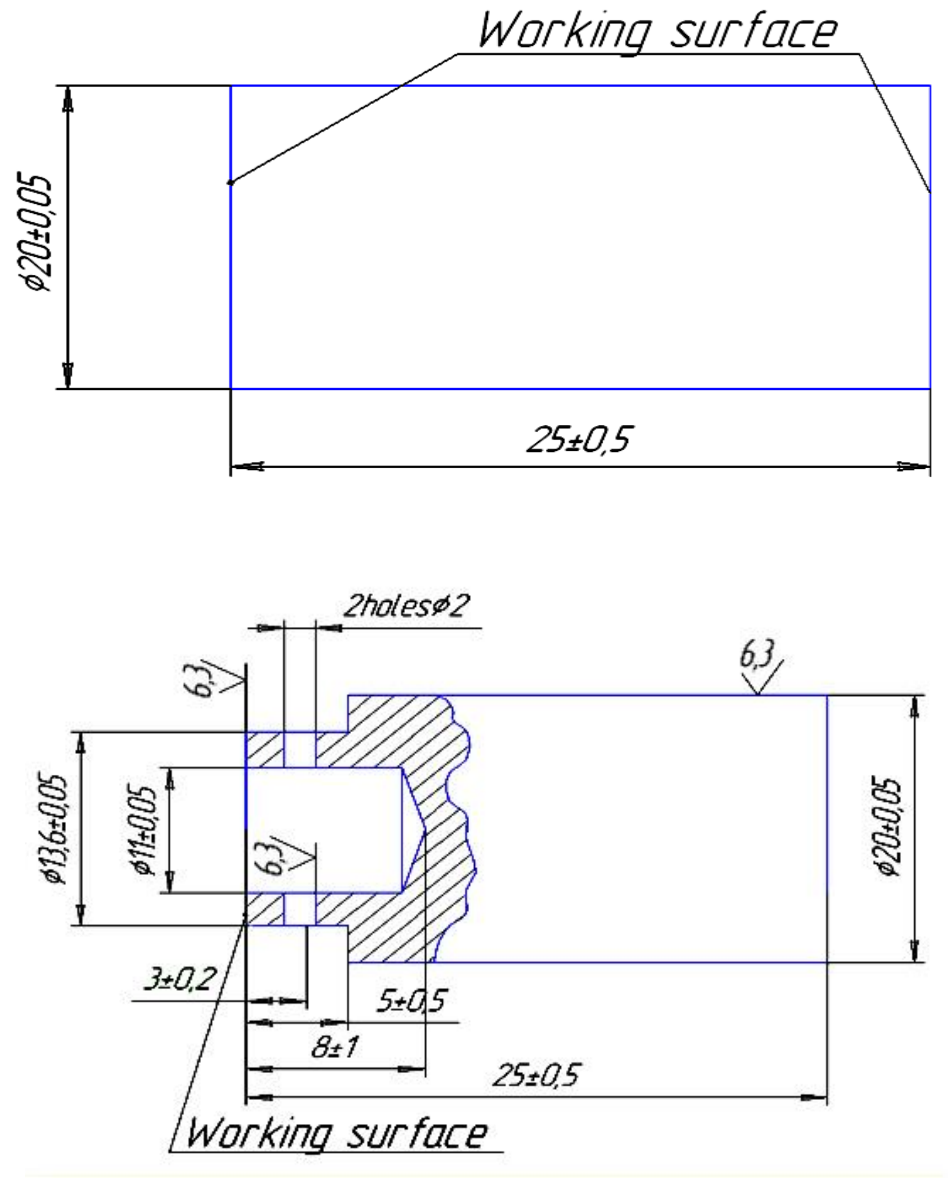


Figure 2.3 - Samples for fretting testing

The control of the temperature of working environment is provided by a thermocouple and pointer of temperature with accuracy ±2 °C, working range of temperatures of chamber 0…200 °C. The set temperature of tests is achieved with the help of a heating element and temperature regulator.

A chamber allows carrying out the experiments in oils and plastic greasings at the temperature from 0 to 200 degrees. Heating is carried out by the increase of tension on latra and heating of nichrome coil. The control of temperature of the liquid environment is carried out through the temperature sensor and milliammeter. The impermeability of the chamber internal cavity is carried out with the help of two rubber temperature and oil resistant sealings.

Measuring of the sample and coating wear have carried out using profilometer depth recorder Калібр-201 of model ГОСТ 19300–86 up to 10 microns and the vertical type optimeter ІКВ more than 10 microns, by taking profilograms of eight equidistant sections of the working surface of the sample in the radial direction.

Thus, the unique unit for materials wear resistance testing at fretting conditions is developed. The unit enables to carry out the comparative tests of fretting of steels, alloys, coverings and composite materials in different liquid and gas environment. Using the standard specimens for fretting - ГОСТ 23.211-80 the unit allows providing tests in the range of loading from 1 to 40 MPa and in the wide range of sliding speeds.

An important advantage of determining the linear depreciation method [24] is that the magnitude of wear does not depend on the ratio of material and possible changes in supply patterns.

Metallography

Metallography is study of the structure of metals and alloys, particularly using microscopic (optical and electron) and X-ray diffraction techniques.

Metal surfaces and fractures examined with the unaided eye or with a magnifying glass or metallurgical or binocular microscope at magnifications less than 10 diameters can reveal valuable information as to the crystalline, chemical, and mechanical heterogeneity. Crystalline heterogeneity is known metallographically as grain. Chemical heterogeneity arises from impurities, segregation of chemical elements, and nonmetallic inclusions. Mechanical heterogeneity consists of local deformations of structure, elongation or distortion of nonmetallic inclusions, and regions of chemical segregation, resulting from cold fabrication processes.

Microscopic examination of polished or etched surfaces at magnifications ranging from about 100 to 1,500 diameters can reveal such information as size and shape of grains, distribution of structural phases and nonmetallic inclusions, microsegregation, and other structural conditions. Metallographic etching—that is, subjecting the polished surface to the action of a corrosive reagent—can reveal the structure by a selective and controlled solution or can unbuild the metal inwardly from the surface. This successive destruction occurs because of the different rates of dissolution of the structural components under the attack of the etching agent. Polarized light is useful to reveal grain structure, detect preferred orientation, examine oxide surface films, and identify phases of different composition [25].

In electron microscopes a beam of electrons instead of a beam of light is directed onto the specimen; because only a highly energetic electron beam will pass through metal films thicker than about 0.05 micron (1 micron equals 0.001 millimetre), a microscope specimen replica of the surface is ordinarily made. To do this a plastic solution is poured over the etched surface; the hardened solution contains on one side a reverse impression of the surface contours of the specimen. The development of transmission electron microscopes, in which the electrons are accelerated to 100 kiloelectron volts or more, has made it possible to examine internal details of thin foils of metals.

X-ray diffraction techniques involve the impingement of a beam of X-rays on the metal specimen and the subsequent diffraction of the beam from regularly spaced planes of atoms; usually, the diffracted rays are recorded on photographic film. The technique is used to study phenomena related to the grouping of the atoms themselves. By measuring the lines or spots on the diffraction pattern and by analysis of the intensity of the deflected rays, information can be obtained about the positionsof the atoms of the specimen and hence the crystallography of the phases, the presence of internal strains, and the presence of solute atoms in solid solutions.

Fractography

Fractography is the study of fracture surfaces of materials. Fractographic methods are routinely used to determine the cause of failure in engineering structures, especially in product failure and the practice of forensic engineering or failure analysis. In material science research, fractography is used to develop and evaluate theoretical models of crack growth behavior.

One of the aims of fractographic examination is to determine the cause of failure by studying the characteristics of a fracture surface. Different types of crack growth (e.g. fatigue, stress corrosion cracking, hydrogen embrittlement) produce characteristic features on the surface, which can be used to help identify the failure mode. The overall pattern of cracking can be more important than a single crack, however, especially in the case of brittle materials like ceramics and glasses [26].

An important aim of fractography is to establish and examine the origin of cracking, as examination at the origin may reveal the cause of crack initiation. Initial fractographic examination is commonly carried out on a macro scale utilising low power optical microscopy and oblique lighting techniques to identify the extent of cracking, possible modes and likely origins. Optical microscopy or macrophotography are often enough to pinpoint the nature of the failure and the causes of crack initiation and growth if the loading pattern is known.

Common features that may cause crack initiation are inclusions, voids or empty holes in the material, contamination, and stress concentrations. "Hachures", are the lines on fracture surfaces which show crack direction. The broken crankshaft shown at right failed from a surface defect near the bulb at lower centre, the single brittle crack growing up into the bulk material by small steps, a problem known as fatigue. The crankshaft also shows hachures which point back to the origin of the fracture. Some modes of crack growth can leave characteristic marks on the surface that identify the mode of crack growth and origin on a macro scale e.g. beachmarks or striations on fatigue cracks. The areas of the product can also be very revealing, especially if there are traces of sub-critical cracks, or cracks which have not grown to completion. They can indicate that the material was faulty when loaded, or alternatively, that the sample was overloaded at the time of failure.

Fractography is a widely used technique in forensic engineering, forensic materials engineering and fracture mechanics to understand the causes of failures and also to verify theoretical failure predictions with real life failures. It is of use in forensic science for analysing broken products which have been used as weapons, such as broken bottles for example. Thus a defendant might claim that a bottle was faulty and broke accidentally when it impacted a victim of an assault. Fractography could show the allegation to be false, and that considerable force was needed to smash the bottle before using the broken end as a weapon to deliberately attack the victim. Bullet holes in glass windscreens or windows can also indicate the direction of impact and the energy of the projectile. In these cases, the overall pattern of cracking is vital to reconstructing the sequence of events, rather than the specific characteristics of a single crack. Fractography can determine whether a cause of train derailment was a faulty rail, or if a wing of a plane had fatigue cracks before a crash.

Fractography is used also in materials research, since fracture properties can correlate with other properties and with structure of materials [27].

Conclusions to part 2

All the technological operations to which the details are exposed prior to coating application, leave traces on the details surface in the form of pollution. So prior to coating application it is necessary to clean the detail surface. The choice of a surface cleaning method depends on many factors, primarily on the nature of contamination and cleanliness requirements of the surface. In this chapter different methods of preparing metal part before coating application were considered. We have proposed the electric-arc evaporator of metals and ionic gas purification system developed by specialists of the NationalScienceCenter "Kharkov Physical-Technical Institute".

The basis of the methods chosen for work contains a study of qualitative parameters of friction pares. Scheme of the contact plane-plane type is used on installation MFK–1. The main advantages of this method are: quick assessment of durability of materials and coatings under fretting, satisfactory reproducibility of test results with a minimum number of test samples, simplicity of the method and corresponding equipment, possibility of smooth control of the frequency and amplitude of normal load micro shifts, tests using plastic and liquid lubricants, registration of friction during testing.

Currently, the aviation industry widely uses solid chrome plating, primarily to improve the durability and corrosion resistance. With regard to internal surfaces, chrome is often used to increase wear and corrosion resistance of the surface of the hydrauliccylinders of aircraft landing gear. With the above described methods for surface cleaning and deposition of coatings on it coatings of vacuum-arc method can be tight vacuum-arc coating thickness to 200 microns with a hardness of from 170 to 700 kg/mm^2. Different structure of the coatings (both columnar and fine-grained) can be obtained.

With regard to environmentally unsound method of galvanic current the actual is the replacement of chromium electroplating with other refractory coatings applied by environmentally clear methods.

PART 3.

TESTING TITANIUM ALLOY BT-22 IN COUPLE WITH OTHER METALS ON SPECIAL MACHINES

3.1 Methodology of the experiment

The aim of the work is to determine wear processes of titanium alloy BT-22 in couple with different alloys used for aircraft design in conditions of fretting-corrosion and determination of most optimal alloy for contact with BT-22.

Fretting-corrosion experiments where held on the machine MFK-1 that imitates vibrations due to contact scheme plane-plane according to GOST 23.211-80. The sense of the method is that cylindrical movable specimen (counterspecimen) that coincides by the edge with immovable cylindrical specimen at given pressure is actuated in cycle-rotational motion with given amplitude and frequency.

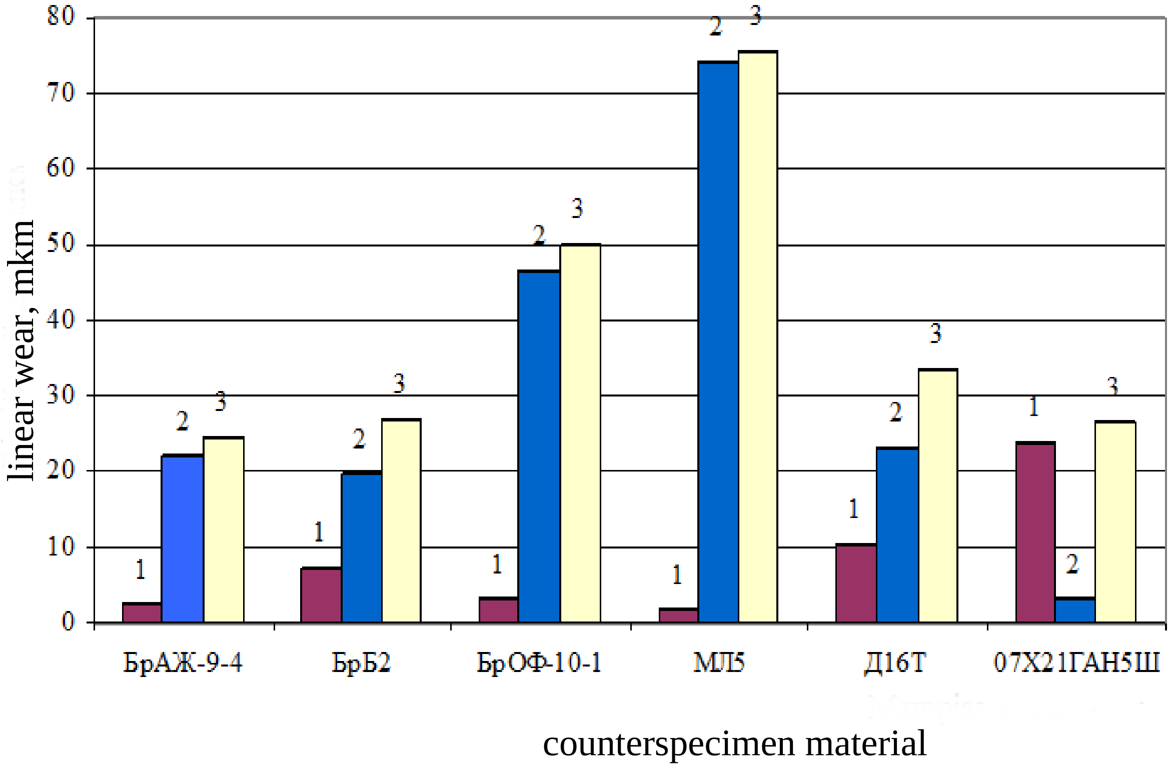
Investigations where held at constant loading 20 MPa and amplitude 130 mkm. Frequency was constant and was equal to 30 Hz. Experimental base corresponded to 500000 cycles. Specimens temperature at the beginning was equal to 293 K. Investigations about linear wear measurement and wear intensity of the layers were held at the air condition under friction without lubricants.

Specimen is the set of cylindrical rollers with 20 mm in diameter, made from titanium alloy BT-22 which is thermally treated by accepted in aviation regime of three-stage treatment, which consists of stabilizing burning, soft hardening on the air with future aging [7]. Counter specimens for investigations where done from alloys БрОФ-10-1, БрБ2, БрАЖ-9-4, МЛ5, Д16Т, 07Х21ГАН5Ш. Materials where selected according to calculation of the most used alloys applied in aviation.

Firstly linear wear of immovable specimen was measured using optimeter IKV of vertical type, for a set amount of cycles. Due to the results we can measure wear ability of the investigated material. Number of experiments was equal to 3 per each experiment.

3.2 Fretting properties of titanium alloy BT-22

Experimental results are described at picture 3.1, that approve that titanium alloy BT-22 wear is in few times less than the wear of investigated colored design materials. The only exception is alloy 07Х21ГАН5Ш which wearability is higher than ВТ-22. That can be explained by high hardness of the alloy based on Nikel concentration and significant fracture of Chromium -21 %. During investigations titanium alloy due to its ability of cold catching was lubricated on the counterspecimen and friction was basically provided between ВТ-22 and ВТ-22.



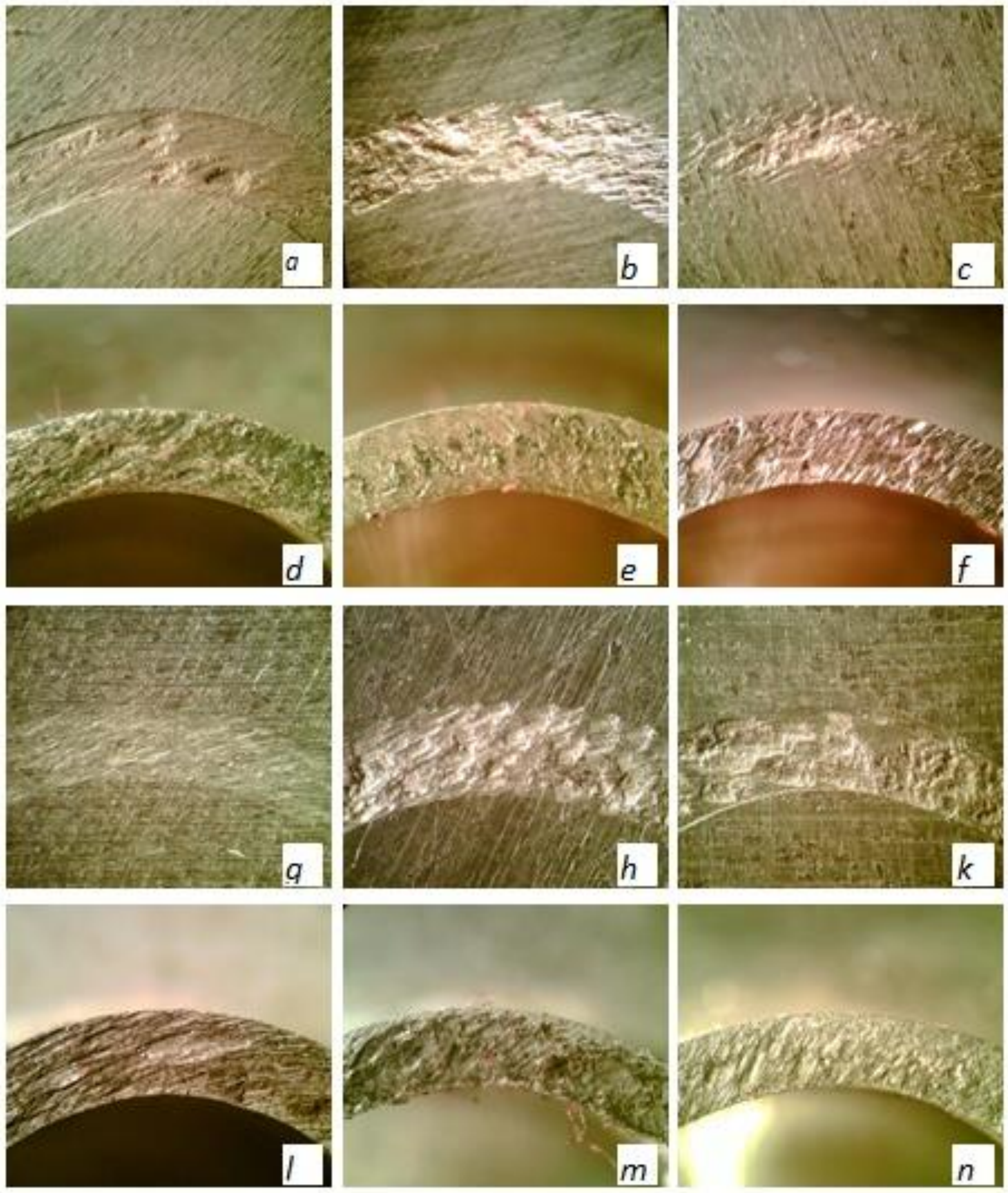
1 – linear wear of titanium alloy ВТ-22, 2 – linear wear of aviation materials, 3 – total wear of wearing couple

Figure 3.1 - Fretting resistance of titanium alloy ВТ-22 (1) during friction with different materials (2) (A – 130mkm, P – 20 Mpa, ν – 30 Hz, T – 293 К, N – 500 000 cycles, environment - air)

According to the data obtained on the graph we can state that most fretting resistant couple is ВТ-22 – МЛ5. Moreover ВТ-22 wear is close to minimal and regarding the counterspecimen – maximal in comparision between all investigated surfaces.

3.3 Analysis of obtained results

Current behaivour is due to soft [28] microdispersed oxides of magnesium alloy МЛ5 which operated as intermidiate layer. This fact is approved by topography of wear surface given on Figure 3.2 and wear coefficient (Table 3.1).



a – ВТ-22 in couple with БрОФ-10-1 (d), b – ВТ-22 in couple with БрБ2 (e), c – ВТ-22 in couple with БрАЖ-9-4 (f), g – ВТ-22 in couple with МЛ5 (l), h – ВТ-22 in couple with Д16Т (m), k – ВТ-22 in couple with 7H21GAN5Sh (n)

Figure 3.2 - Friction topography of immovable (a, b, c, g, h, k) and movable (d, e, f, l, m, n) specimens at fretting-corrosin testing (A – 130 mkm, P – 20 MPa, ν – 30 Hz, T – 293 K, N – 500 000 cycles, environment - air)

During experiments at couple Д16Т – ВТ-22 occurs significant wear of titanium alloy due to oxidizing of aluminium surface and creation of rigid abrasive parts of Al_2O_3 at wear area. Such situation is repeated while wearing of couple БрБ2 – ВТ-22 though its not seen so well enough. Berilium oxides – BeO have less hardness, around 13 000 Mpa and size less than corundum , which hardness is up to 25 000 MPa [8]. As a result on the titanium surface as well as on counterspecimen occurs intensive abrasive wear, approved by friction surface topography at Fig. 3.2.

High wear of material БрОФ-10-1 is explained by tin fracture in bronze which is smeared on the alloy ВТ-22 surface while friction and oxidizes intensively.

At Fig. 3.2 there are given traces of tested materials and titanium alloy ВТ-22 after helding the experiments. We can see from the Fig.s, that there are 3 basical types of failures on the friction surfaces [9]:

1. Pit destruction.
2. Furrowed distruction from the merger of the pits.
3. Macropit destruction.

In general case pit destruction can be divided into 2 stages of forming pit destruction. First stage – appearance of scaly peeling of thin surface layers. The second stage of pit destruction is the appearance of typical pit of destruction in certain areas, which later merged into the groove (Figure3.2. b, h, e). Analysis of grooves formation shows that the pit destruction is the main factor in damage development. The side surfaces of the pits have typical kvazicrystal, with a high degree of plastic deformation or intergranular destruction.

Furrowed distruction is the result of pit joining. Furrows form in the micromovement direction and are located equidistantly from each other. There can be designated two traces types: first – diaphragms between pits haven’t been destroyed yet (Figure 3.2. h) and second one – formed furrow (Figure 3.2. g), which have pretty smooth surface. It was obtained as a result of long-time operation of separeted parts in conditions of corrion activity.

Macropit destruction describes strong destructions of the material and is the result of fatigue and corrosion of the surface (Figure 3.2. b, f). Basic danger is concentrated in intensive surface damages represented by micro cracks, strengthening zones and restrengthening of material. Besides such destruction type corresponds to maximal damages (Fig. 3.1.).

At table 3.1. there are given set coefficients for titanium alloy coefficient BT-22 in copule with aviation colored design alloys after 300 000 and 500 000 cycles.

Table 3.1 - Friction coefficient for titanium alloy BT-22 in couple with aviation materials depending on operational time

Operation N, cycles	Counterspecimen material					
	БрАЖ-9-4	БрБ2	БрОФ-10-1	МЛ5	Д16Т	07Х21ГАН5Ш
300000	0,22	0,28	0,28	0,14	0,33	0,19
500000	0,20	0,25	0,25	0,12	0,22	0,17

The maximum friction coefficient while frictions with material Д16Т due to action of abrasive particles. The minimum friction coefficient is seen in couple BT-22 – МЛ5. It is explained by action of intermediate microdispersed oxides of intensively worn alloy МЛ5. Couples BT-22 – БрБ2 and BT-22 – БрОФ-10-1 show intermediate results between BT-22 – БрАЖ-9-4 and BT-22 – Д16Т due to higher activity for surface catching of alloy БрБ2.

Conclusions to part 3

After analysing the tests that where occurred – we can make following conclusions:

1. Oxides hardness during materials testing on fretting resistance significantly influences on processes that occur in friction zone and on quantity of wearing , determines leading mechanism of wearing.
2. Selection of contact materials need to be held according to few factors: summary wear, possibility of resumption or replacing of failured detail after cycles of friction. For example at almost equal summery wear of worn couples: ВТ-22 - 07Х21ГАН5Ш and ВТ-22 – БрБ2 wear of meterials significantly differs.
3. Regarding the recommendation about which material to choose in couple with titanium alloy ВТ-22 the best one to use is БрАЖ-9-4

PART 4.

LABOUR PRECAUTION

4.1 Legislative and normative acts of Ukraine on labor precaution

Legislation on labour precaution of Ukraine consists of the normative acts, which regulate the mutual relations between different subjects of the right in sphere of labour precaution.

Ukrainian Law About Labour Precaution defines a regulation for realization of constitutional right of the citizens on protection of their life and health during labour activity, regulates in participation of appropriate State organs the relationships between enterprise proprietor, establishment and organizations or its representative organ and worker in safety questions, working hygiene and occupational environment and installs single organization order of labour precaution in Ukraine.

In article 43 of the Constitution of Ukraine it is proclaimed that everyone has the right for work, which is freely chosen, has safe and healthy conditions and the law doesn’t less define salary for it.

In article 45 of the Constitution it is proclaimed everyone who works, masses a right to rest. This right is provided with granting days of weekly rest, and also paid annual vacation, establishment of shortened working hours for separate professions and the productions, the reduced period of operation at night.

In article 46 of the Constitution it is specified that citizens have the right for the social protection, including right for providing them in case of full, partial or temporary disability, loss of the supporter, unemployment owing to circumstances, and also in old age and in other cases provided by the law.

The law of Ukraine "About labor precaution"installs single organization order of labour precaution in Ukraine. Also it defines a regulation for realization of constitutional right of the citizens on protection of their life and health during labour activity. It legal bases and guarantees of implementation of the right by citizens of Ukraine to dispose of the abilities to productive and creative activity.

Regulations, which regulate the works in the sphere of aviation, especially during diagnostics of aircraft’s power unit:

- ДСТУ 3464-96 Aviation fuel, oils, technical solutions.
- ДСТУ 5467-09 Non destructive control methods. Classification and certification of personnel in the sphere of non destructive control. Basic requirements
- ДСТУ 3228-95: Civil aerodromes. Terms and definitions
- ДСТУ 2862-94 Technical equipment reliability. Methods of characteristics calculation. Main requirements.
- НПАОП 63.23-1.06-98 Safety rules for maintenance and repair of aircraft.
- ДСТУ Б ГОСТ 28574:2011 Corrosion protection in aviation.
- ГОСТ 20296-81 Civil aviation aircraft. Acceptable levels of noise in the cabin and methods of their measurement.
- ДСТУ 2388-94 Aircraft ventilation systems. Basic requirements.

4.2 Dangerous and harmful factors during operation and maintenance for mechanical engineer

The Object of labour precaution is – laboratory, Subject – mechanical engineer.

Harmful and dangerous factors are determined by the standard [26] and subdivided on: physical, chemical, biological and psycho-physiological. Physical, chemical, biological groups are divided into concrete dangerous and harmful production factors. Psycho-physiological group in accordance with nature of influences is subdivided into physical and nervously psychic overloads.

Here is a list of physical harmful and dangerous substances at constructor work fulfillment in the design-engineering laboratory:

- increased level of electromagnetic radiation from computers;
- high voltage in the electric wiring, dangerous short circuit may occur;
- decreased air movement in the room;
- increased level of static electricity;
- shortage of natural lightening;
- direct and reflected gleam;
- not sufficient lightening of working place;

- rough and sharp surfaces;
- furnishing made of low quality or toxic materials;
- increased level of infrasonic, ultrasonic oscillations;
- potential to dust formation;

There is other kind of harmful and dangerous substances, what is psychophysical. It influences human psychical state, what in turn influences its quality of work performed. Here are some factors influencing constructor at his workplace:

- static physical overloading (sitting position during working day);
- mental strain (concentration);
- overload of sense organs (eyes);
- monotonous work;
- emotional stresses.

Levels of dangerous and harmful factors must not exceed the maximum permissible significance, established in sanitary standards, regulations and normatively-technical documentation.

4.3 Technical and organizational measures for reducing exposures of hazards and harmful factors

In order to ensure stuff safe work safety measures in the operation and maintenance should be improved. These measures include the calculation of operational loads that can occur when probable accidents.

The remote control is defined in the block and is located in the zone of destruction probable destruction of the engine and supercharger, making the ability to protect staff from a number of harmful and dangerous factors defeat parts and supercharger drive at their destruction and scattering. In addition, the turbine and compressor unit cylinder primary compartments separated by a wall and a closed guard, which also acts as a heat shield and noise reduction parts.

To create comfortable conditions of staff in the project included an air conditioning system. This system can work both in normal and in emergency mode.

To reduce noise of air intake and exhaust devices of engine apply special mufflers. The wall of the container all units of the unit are made of special panels filled with sound absorbing material.

At work stations cannot exclude the probability of loss of the transported gas may cause explosion and emergency and injuries to staff. To prevent such incidents laboratory must be equipped by gas detectors and gas losses alarm. The station should be in sets of personal respiratory protection and personnel must be trained to use them.

4.3.1 Laboratory lighting calculation

Artificial light is an important aspect in engineering work. Lighting system mounted correctly and calculated according to room scale saves humans health, don’t waist energy and save money.

System of combined illumination is more economical and allows creating high illumination in workplaces. System of general illumination is more preferable from point of view of labour hygiene, because it allows creating uniform illumination distribution in whole apartment, to make away sharp shades and contrasts.

In most of cases a computation of industrial illumination is fulfilled for use method of light flux. Initial data is represented in table 4.1

Table 4.1 - Initial data for calculation of lighting in the working are

Name	Index and value
Illumination norm for departments	En = 200l x
Height of the workplace	H = 4 m
Length of the hangar, that is enlightened	A = 28 m
Width of the hangar, that is enlightened	B = 8 m
Lamp height over work surface	Hp = 2 m
Hangar area	S = 300 m2
Assurance factor of light flux	K = 1.25
Reflection coefficients for: ceiling	pc = 0.9
walls	ρw = 0.6
spotlighted surface	ρs = 0.2

Calculation of the general illumination of the hangar apartment.

Workplace index is calculated by:

$$\varphi = \frac{A \cdot B}{h_p \cdot (A+B)} = \frac{28 \cdot 8}{2 \cdot (28+8)} = 3{,}1$$

Coefficient of light flux use from lamp η=61

Let’s choose NC-2A418C lamp, luminous flow F = 1150lx.

$$n = \frac{E_n \ \cdot S \cdot k \cdot Z}{F \cdot \eta} = \frac{200 \cdot 300 \cdot 1.25}{1400 \cdot 0.9} = 79$$

Number of lamps in workplace n = 81;

Total power of lighting installation is 81 kW;

In this case the disposition of lamps should be uniformly placed in 9 rows, 9 in each row.

4.4 Fire and explosion safety at maintenance facilities

The approach for fire and explosion identification and prevention is same approach as that used in general health and safety legislation.

It is possible to identify the potential ignition sources in the laboratory by looking for possible sources of heat which could get hot enough to ignite material found in the laboratory. These sources could include:

- smokers material, e.g. cigarettes, matches and lighters;
- electrical, gas or oil-fired heaters (fixed or portable);
- naked flames, e.g. candles or gas or liquid-fuelled open-flame equipment;
- hot processes, e.g. welding by contractors or shrink wrapping;
- cooking equipment (electric kettle);
- faulty or misused electrical equipment;
- lighting equipment, e.g. halogen lamps or display lighting too close to stored products;

– hot surfaces and obstruction of equipment ventilation, e.g. laboratory equipment;

– arson.

Indications of ‘near-misses’, such as scorch marks on furniture or fittings, discolored or charred electrical plugs and sockets, cigarette burns etc., can help you identify hazards which you may not otherwise notice.

Having identified the fire hazards, it is needed to remove those hazards if reasonably practicable to do so. If is not possible to remove the hazards, reasonable steps to reduce them should be taken. This is an essential part of fire risk assessment and as a priority this must take place before any other actions.

Ensure that any actions taken to remove or reduce fire hazards or risk are not substituted by other hazards or risks. For example, if you replace a flammable substance with a toxic or corrosive one, you must consider whether this might cause harm to people in other ways.

There are various ways that to reduce the risk caused by potential sources of ignition, for example:

– wherever possible replace a potential ignition source by a safer alternative;

– replace naked flame and radiant heaters with fixed convector heaters or a central heating system. Restrict the movement of and guard portable heating appliances;

– separate ignition hazards and combustibles e.g. ensure sufficient clear space between lights and combustibles;

– operate a safe smoking policy in designated smoking areas and prohibit smoking elsewhere;

– ensure electrical and mechanical and gas equipment is installed, used, maintained and protected in accordance with the manufacturer’s instructions.

– check all areas where hot work (e.g. welding) has been carried out to ensure that no ignition has taken place or any smoldering materials remain that may cause of fire.

– ensure that no-one carrying out work on gas fittings which involves exposing pipes that contain or have contained flammable gas uses any source of ignition such as blow-lamps or hot-air guns.

– take precautions to avoid arson.

Conclusion to part 4

In this diploma part main laws of Ukraine on labour precaution are described, represented some normative acts, analyzed harmful and dangerous substances at aircraft maintenance, calculated necessary illumination for working area and fire protection measures at aircraft maintenance are analyzed.

Legislation of Ukraine provides laws for labour precaution in order to regulate labour work for health protection of the workers. In order to decrease the influence of these harmful and dangerous factors was provided the general safety requirements that are necessary for implementation.

PART 5.

ENVIRONMENTAL PROTECTON

5.1. Harmful factors of aviation influence on environment

Aircraft produce the same types of emissions as your automobile. Aircraft jet engines, like many other vehicle engines, produce carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), carbon monoxide (CO), oxides of sulfur (SO_x), unburned or partially combusted hydrocarbons (also known as volatile organic compounds (VOCs)), particulates, and other trace compounds. A small subset of the VOCs and particulates are considered hazardous air pollutants (HAPs). Aircraft engine emissions are roughly composed of about 70 percent CO_2, a little less than 30 percent H_2O, and less than 1 percent each of NO, CO, SO_x, VOC, particulates, and other trace components including HAPs. Aircraft emissions, depending on whether they occur near the ground or at altitude, are primarily considered local air quality pollutants or greenhouse gases, respectively.

Water in the aircraft exhaust at altitude may have a greenhouse effect, and occasionally this water produces contrails, which also may have a greenhouse effect. About 10 percent of aircraft emissions of all types, except hydrocarbons and CO, are produced during airport ground level operations and during landing and takeoff. The bulk of aircraft emissions (90 percent) occur at higher altitudes. For hydrocarbons and CO, the split is closer to 30 percent ground level emissions and 70 percent at higher altitudes.

Aircraft are not the only source of aviation emissions. Airport access and ground support vehicles produce similar emissions. Such vehicles include traffic to and from the airport, ground equipment that services aircraft, and shuttle buses and vans serving passengers.

Other emissions sources at the airport include auxiliary power units providing electricity and air conditioning to aircraft parked at airport terminal gates, stationary airport power sources, and construction equipment operating on the airport.

Emissions from Combustion Processes

CO_2 - Carbon dioxide is the product of complete combustion of hydrocarbon fuels like gasoline, jet fuel, and diesel. Carbon in fuel combines with oxygen in the air to produce $C0_2$.

H_2O - Water vapor is the other product of complete combustion as hydrogen in the fuel combines with oxygen in the air to produce H_20.

NO_x - Nitrogen oxides are produced when air passes through high temperature/high pressure combustion and nitrogen and oxygen present in the air combine to form NO_x.

HC - Hydrocarbons are emitted due to in complete fuel combustion. They are also referred to as volatile organic compounds (VOCs). Many VOCs are also hazardous air pollutants.

CO - Carbon monoxide is formed due to the incomplete combustion of the carbon in the fuel.

SO_x - Sulfur oxides are produced when small quantities of sulfur, present in essentially all hydrocarbon fuels, combine with oxygen from the air during combustion.

Particulates - Small particles that form as a result of incomplete combustion, and are small enough to be inhaled, are referred to as particulates. Particulates can be solid or liquid.

Ozone – O_3 is not emitted directly into the air but is formed by the reaction of VOCs and NO_x in the presence of heat and sunlight. Ozone forms readily in the atmosphere and is the primary constituent of smog. For this reason it is an important consideration in the environmental impact of aviation.

Aviation emissions reflect the level of overall aviation activity. The growth of air travel for the past several decades has been very rapid. Demand for travel services, both passenger travels and freight transportation, is increasing substantially.

It is widely acknowledged that man-made emissions of carbon dioxide and other greenhouse gases are causing major changes to the planet's climate. The global average surface temperature of the earth has increased by 0.6 °C during the 20th century and is predicted to increase by between 1.8 and 5.8 °C by the year 2100. By contrast, the last ice-age was 5 °C cooler than the present 'warm-period'. These future temperature rises will have severe climate impacts, with higher local maximum temperatures, fewer cold days, more heavy rain, summer droughts, decreased snow cover and sea ice, rising sea levels an increase in storm intensity all deemed likely. The societal impacts of these changes are also likely to be severe.

The acceptance of the fact that much of the observed and predicted future climate change is due to human activity has led to a desire to reduce greenhouse gas emissions, so as to minimize the impacts of climate change on society and individuals. The response has been far-reaching, with the international community, and concerned businesses and individuals, seeking methods to minimize emissions. At the international level, the Kyoto Protocol came into force in February 2005, and commits signatories to legally binding emissions targets. Industrialized countries must reduce their total emissions by 5.2 % of 1990 levels by 2010 (actually an average of the period 2008-2012). The UK is committed to reducing its emissions by 12.5 % below 1990 levels by 2010.

Individuals and businesses have also expressed a desire to reduce their own emissions beyond the requirement of policy, which has led to the principle of offsetting. An individual pays to offset their own personal emissions - the money raised will fund energy efficiency or renewable energy projects which lead to a reduction in greenhouse gas emissions equal to the amount offset.

In order for offsetting to be credible, the greenhouse gas emissions to be offset have to be calculated accurately, and the projects require equally rigorous verification to ensure that the savings are in fact made. Carbon dioxide emissions from activities within the home, business, or terrestrial transport can be simply calculated by knowing the amount of fuel burned for the given activity. However, greenhouse gas emissions from flights require a special approach, which is outlined in this report.

Aviation emissions have a greater climate impact than the same emissions made at ground level. This is because emissions at altitude can instigate a host of chemical and physical processes that have climate change consequences. This is identified through the use of a multiplier, known as a 'metric' to account for the greater climate impacts of aviation.

The basic methodology for calculating the impact of aviation emissions is merely the mass of carbon dioxide emitted multiplied by the chosen metric. Once this extra impact has been accounted for, the emissions may be cost in the usual manner.

Aircraft noise is noise pollution produced by any aircraft or its components, during various phases of a flight: on the ground while parked such as auxiliary power units, while taxiing, on run-up from propeller and jet exhaust, during takeoff, underneath and lateral to departure and arrival paths, over-flying while en route, or during landing.

A moving aircraft including the jet engine or propeller causes compression and rarefaction of the air, producing motion of air molecules. This movement propagates through the air as pressure waves. If these pressure waves are strong enough and within the audible frequency spectrum, a sensation of hearing is produced. Different aircraft types have different noise levels and frequencies. The noise originates from three main sources:

- aerodynamicnoise;
- engine and other mechanical noise;
- noisefromaircraftsystems.

Aerodynamic noise arises from the airflow around the aircraft fuselage and control surfaces. This type of noise increases with aircraft speed and also at low altitudes due to the density of the air. Jet-powered aircraft create intense noise from aerodynamics. Low-flying, high-speed military aircraft produce especially loud aerodynamic noise.

The shape of the nose, windshield or canopy of an aircraft affects the sound produced. Much of the noise of a propeller aircraft is of aerodynamic origin due to the flow of air around the blades. The helicopter main and tail rotors also give rise to aerodynamic noise. This type of aerodynamic noise is mostly low frequency determined by the rotor speed.

Typically noise is generated when flow passes an object on the aircraft, for example the wings or landing gear. Therearebroadlytwomaintypesofairframenoise:

- Bluff Body Noise - the alternating vortex shedding from either side of a bluff body, creates low pressure regions (at the core of the shed vortices) which manifest themselves as pressure waves (or sound). The separated flow around the bluff body is quite unstable, and the flow "rolls up" into ring vortices - which later break down into turbulence.
- Edge Noise - when turbulent flow passes the end of an object, or gaps in a structure (high lift device clearance gaps) the associated fluctuations in pressure are heard as the sound propagates from the edge of the object (radially downwards).

Much of the noise in propeller aircraft comes equally from the propellers and aerodynamics. Helicopter noise is aerodynamically induced noise from the main and tail rotors and mechanically induced noise from the main gearbox and various transmission chains. The mechanical sources produce narrow band high intensity peaks relating to the rotational speed and movement of the moving parts. In computer modelling terms noise from a moving aircraft can be treated as a line source.

Aircraft Gas Turbine engines (Jet Engines) are responsible for much of the aircraft noise during takeoff and climb, such as the *bass noise* generated when the tips of the fan blades reach supersonic speeds. However, with advances in noise reduction technologies - the airframe is typically more noisy during landing.

The majority of engine noise is due to Jet Noise - although high bypass-ratio turbofans do have considerable Fan Noise. The high velocity jet leaving the back of the engine has an inherent shear layer instability (if not thick enough) and rolls up into ring vortices. This of course later breaks down into turbulence. The SPL associated with engine noise is proportional to the jet speed (to a high power) therefore, even modest reductions in exhaust velocity will see a large reduction in Jet Noise.

Cockpit and cabin pressurization and conditioning systems are often a major contributor within cabins of both civilian and military aircraft. However, one of the most significant sources of cabin noise from commercial jet aircraft, other than the engines, is the Auxiliary Power Unit (APU), an on-board generator used in aircraft to start the main engines, usually with compressed air, and to provide electrical power while the aircraft is on the ground. Other internal aircraft systems can also contribute, such as specialized electronic equipment in some military aircraft.

5.2 Calculation of emission parameters of engine CFM-56

Aircrafts are the non-stationary organized sources of harmful substances (HS) emission in the atmosphere. At formulation and control of plans fulfillment of the protection of nature at the civil aviation (CA) enterprises are taken into account oxide carbon *(CO)*, not burned down hydrocarbon *(CH)*, nitrogen oxides (NO_x), oxides of sulfur (SO_x) and firm particles.

Harmful substances (HS) emission in an aerosphere with spent gases of aircraft engines is determined by issue characteristics of engines, operational mode and operating times on each mode, and also quantity of working engines. Harmful substances (HS) emission consists of emissions in region of the airport, which influences on the local air pollution, and emission at the route flight, which introduces pollution to the upper troposphere layer.

The purpose of the given calculation is definitions of harmful substances (HS) weight, which arrived in an aerosphere at aircraft engines work.

Structure of component *CO* in spent gases of aircraft engines are caused of incomplete combustion of fuel in the engine, which depends on characteristics of its combustion chamber and engine working mode.

The structure of component NO_x in spent gases of an aircraft engine depends on value of mixture temperature in the combustion chamber (than it more, that more forms NO_x), and it maximum (reaches 2500… 3000 *K)* on the take-off mode, and staying time of mixture in the combustion chamber (than it is more, that more forms NO_x), and it occurs on small speeds of airplane flight.

It is obvious, that in airport zone emission depends on a idle mode of its work and from an operation time on this idle mode.

In table 5.1 there are statistical data, the running time on different stages for the modern aero-engines.

In the table 5.1 average values of parameters ($\overline{R}$ and t) for the big airports of the world are given.

Table 5.1 - Engine relative thrust depending on the work mode

№ ofmode	The name of engine operating mode	Relativethrust, $\overline{R}$	Duration of the mode t,minutes
1	Idle mode (idling) in a time of taxiing before take-off	0,07	15
2	Take-offmode	1	0,7
3	Theclimbcondition (1000 m)	0,85 (or 0,9 facevalues)	2,2
4	Themodeoflanding	0,3 (or 0,42 facevalues)	4
5	Idle mode (idling) in a time of taxiing after landing	0,07	7

Here $\overline{R} = \frac{R}{R_O}$, where R - engine thrust on the given mode, R_O - engine thrust on the take-off mode (maximum thrust).

As we see from the table, the most continuous and ecologically dangerous is idle mode. The meaning the thrust value on this mode for modern aircraft engines makes 3%… 9 % from its maximum value R_O.This mode is used in a time of taxiing of the aircraft before take-off and after landing, and also in time of the engine warming-up after start.

Determining in a time of certification tests indexes of emission of harmful substances on the corresponding engine operating mode, find monitoring parameter of emission $\frac{M_i}{R_o}$ of the tested engine that is established ICAO.

This parameter characterizes so-called “degree of harm” engine. In it: M_i - weight in grams of emission of this ***i*** harmful substance (component) for some certain engine operating time, R_o - engine take-off thrust in kiloNewtons.

“The degree of harm” of each aircraft engine is characterized, as has been said above, its monitoring parameters of emission on different components $\frac{M_i}{R_o}$. I.e. the problem from emission calculation of the engine is reduced to definition of each component weight ejected from the engine on a certain time of its work, M_i (if R_O - engine thrust on an take-off idle mode - the value known under the documentation, in particular from the data card of the engine). We shall calculate value M_i for airport zone, for those idle modes and for that period of time its work while the aircraft is in this zone with working engines.

And the aircraft in airport zone as a minimum makes take-off and landing cycle (TLC) of flight, which will consist of such stages:

- Start and warming-up of the engine;
- Taxiing on a line-up take-off position;
- Climb 1000 m;
- Decrease from an altitude 1000 m;
- Run;
- Taxiing up to a shutdown of the engines.

Ground operations are the engine start-up, warming-up, taxiing of the airplane before take-off and after landing.

The full characteristic of these operations (from the point of view of the engine emission calculation) is that engines of an aircraft are working: on one idle mode – idle mode (idling), and on a time is the most continuous operations in airport zone. These are condition simplifies calculations.

Operations landing - take-off - landing is the take-off, climb on 1000 m, decent from an altitude 1000 m and landing.

In this case for calculation of the airplane engine emission which is in air, the emission characteristic is mass speed of emissionW_i(kg$_{\text{ingr}}$./h), (instead of an index of emission) which shows, how many the given harmful substance deposits on the given engine operating mode for unit of time.

$W_i$also it is determined in a time of the engine certification tests.

Then definition$M_{ВП}$is calculated by formula:

$$M_{ВП} = W_{i1} \times T_{ВП} + W_{i2} \times T_{ВП} + W_{i3} \times T_{ВП},$$

Where:$W_{i1,2,3}$ – mass speed of component emission I at the corresponding engine operating mode accordingly on take-off, in time to climb 1000 m and in a time of decent from the altitude 1000 m,

Values$t_{МГ}$, $T_{1,2,3}$are taken from the above-stated table of engine operating modes in airport zone.

Having calculated thus $M_i = M_{iH} + M_{ВП}$, to calculate monitoring parameter of engine emission $\frac{M_i}{R_o}$ and to compare it with ICAO standards, is making conclusion about conformity of the given engine to the modern demands on emission in relation to the given component.

The same calculation to make on all main components.

Calculation of monitoring parameters of the engine emission CFM-56 on airplane Boeing 737-800 with components CO andNO_x and to make the conclusion on correspondence of these engines to modern ICAO demands.

Initial data:

- Engine thrust of the CFM-56: R_0 =105 кN; R_{idle} =7.35 кN;
- Engine specific consumption CFM-56: $C_{тр\ тг}$ = 0,061 kg / hour;

Using table 5.2, determine value of the emission factor (emission index) and mass speed of the emission of the component for the engine CFM-56, on the airplanes Boeing 737-800.

Table 5.2 - Emission parameters of engine CFM-56

$K_{Сон}$ =0,031 $кg_{ingr}/кg_{fuel}$	$W_{Сон1}$=12.2 кg/h	$W_{Сон2}$=10.2 кg/h	$W_{Сон3}$=19.1 кg/h
K_{NOx}=0,0049 $кg_{ingr}/кg_{fuel}$	W_{Nox1}=104 кg/h	W_{Nox2}=76 кg/h	W_{Nox3}=12 кg/h

From the table 5.1 of engine operating mode in airport zone we have:

$$T_{idle} = 15 + 7 = 22 \text{minutes} = 0{,}367 \text{ h}$$

$$T_{1з\text{-}п} = 0{,}7 \text{minutes} = 0{,}0117 \text{ h}$$

$$T_{2з\text{-}п} = 2{,}2 \text{minutes} = 0{,}0367 \text{ h}$$

$$T_{3з\text{-}п} = 4 \text{ minutes} = 0{,}067 \text{ h}$$

So Calculation of mass of annual blowouts CO and NO_x we see on formula :

$$M_1 = M_{1H} + M_{1ВП} \,,$$

$$M_2 = M_{2H} + M_{2ВП} \,,$$

where $M1_H$, $M2_H$ - the mass of harmful substances respectively CO and NO_x, which jump out time of land operations (start, idle running and a taxiing, before splash and after landing - modes 1, 5); $M1_{ВП}$, $M2_{ВП}$ - the mass of harmful substances respectively CO and NO_X, which jump out time of runway operations (take-off, ascent of 1000 m, on landing of height of 1000 m - modes 2, 3, 4).

$$M_{1H} = K_1 C_{ПВИТМГ} R_{МГ} T_{МГ},$$

$$M_{2H} = K_2 C_{ПВИТМГ} R_{МГ} T_{МГ}$$

$$M_{1H} = 0{,}312 \times 0{,}061 \times 7{,}35 \times 99{,}09 = 1{,}38 \text{ kg}$$

$$M_{2H} = 0{,}049 \times 0{,}061 \times 7{,}35 \times 99{,}09 = 0{,}22 \text{ kg}$$

$$M_{Сон} = 0{,}012 \times 45{,}08 = 0{,}54 \text{ kg}$$

$$M_{Nox} = 0{,}0028 \times 45{,}08 = 0{,}12 \text{ kg}$$

$$M_{1ВП} = 3 \times (0{,}14 + 10{,}2 \times 0{,}0367 + 19{,}1 \times 0{,}067) \times 90 = 0{,}480 \text{ kg}$$

$$M_{2ВП}= 3 \times (104 \times 0{,}0117 + 76 \times 0{,}0367 + 12 \times 0{,}067) \times 90 = 1{,}294 \text{ kg}$$

$$M_1 = 1{,}38 + 0{,}480 = 1{,}025 \text{ kg}$$

$$M_2 = 0{,}22 + 1.294 = 1{,}514 \text{ kg}$$

We consider mass of emissions for three engines and annual quantity of take-offs - landings (90 take-offs - landings):

$$M_1 = 1025 \times 3 \times 300 = 922\ kg$$

$$M_2 = 1514 \times 3 \times 300 = 1362{,}6\ kg$$

Comparing to ICAO standards:

$$M_1/R_0 = 1025/105 = 10 \text{ g/кN} < 118 \text{ g/кN}$$

$$M_2/R_0 = 1514/105 = 15{,}5 \text{ g/кN} < 80 \text{ g/кN}$$

Conclusion to part 5

After the calculation of the value of released pollute substances in g/kN, first of all, the mass of released pollute substances which are thrown out from the air gas-turbine engine in a structure of waste gases, in a run time of a take-off and landing cycle should meet the ICAO rules for emission and ecology protections.

Calculations shows, that engine CFM-56 by the emission characteristics satisfies norms of ICAO.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

In order to analyze all the keypoints of my diploma project it is necessary to summarize all information above and to make general conclusions, that are based on diploma investigation and laboratory tests.

Firstly it is necessary to understand that fretting-corrosion is absolutely negative effect, that can spoil the materials and reduce aircraft safety in general. Fretting corrosion refers to corrosion damage at the asperities of contact surfaces. This damage is induced under load and in the presence of repeated relative surface motion, as induced for example by vibration. Pits or grooves and oxide debris characterize this damage, typically found in machinery, bolted assemblies and ball or roller bearings. Contact surfaces exposed to vibration during transportation are exposed to the risk of fretting corrosion.

Damage can occur at the interface of two highly loaded surfaces which are not designed to move against each other. The most common type of fretting is caused by vibration. The protective film on the metal surfaces is removed by the rubbing action and exposes fresh, active metal to the corrosive action of the atmosphere.

In order to prevent all possible damages it is recommended to use titanium alloys, where lifecycle is much longer than for regular metals used in aviation. Though we need to understand that titanium alloy has its own durability and operational time. Hence we need to improve material couples, such as titanium and other metals or steels.

Analyzing test machines that imitate details wear at the conditions of cycle friction we determined that machine MFK-1 is the most suitable and appropriate for obtaining required results of titanium alloys and other aviation materials friction and wear.

After analysing the tests that where occurred we can make few conclusions about the right usage of titanium alloys in a couple.

Oxides hardness during materials testing on fretting resistance significantly influences on processes that occur in friction zone and on worn area, determines leading mechanism of wearing. Selection of contact materials need to be held according to few factors: summary wear, possibility of resumption or replacing of failured detail after cycles of friction. For example at almost equal summery wear of worn couples: ВТ-22 - 07Х21ГАН5Ш and ВТ-22 – БрБ2 wear of meterials significantly differs.

Currently, speaking about Ukrainian manufactury the serial aircraft is AN-148. In case of deeper analysis of this aircraft we can say that almost all assembleys of the landing gear are made of titanium alloy in couple with other colored aviation materials.

Regarding the recommendation about which material to choose in couple with titanium alloy ВТ-22 the best one to use is БрАЖ-9-4. Such replacing of materials that were used before will lead to cost reduction for aircraft manufacturing and maintenace, because they are financially cheaper. At the same time we don’t lose in quality of the units and links, because our recommendations are based on the tests that underline the reliability of the chosen couples of alloys. So we recommend to replace existing alloy couples on plants and design officies that are using older design methods applying 30ВХГСА as an example.

REFERENCES

1. R.B. Waterhouse. Friction in the Transport Industry - Proceedings of the 6th European Congress on Metallic Corrosion, 15-22 Sept 1977, London.
2. Титан. Металловедение и технология. Тр. III Международная конференция по титану М. ВИЛС, – 1978, т.1. – 585с., т.2. – 798с.
3. Society of Tribologists and Lubrication Engineers. Basics of friction URL. – Access mode: http://www.stle.org/resources/lubelearn/friction/
4. X. Zhang, C. Zhang, C. Zhu. Slip Amplitude Effects and Microstructural Characteristics of Surface Layers in Friction Wear of Carbon Steel - Wear, Vol 134, 1989, p 187-209.Society of Tribologists and Lubrication Engineers. Basics of friction URL. – Access mode: http://www.stle.org/resources/lubelearn/friction/.
5. Iwabuchi and R.B. Waterhouse. The Effect of Ion Implantation on the Friction Wear of Four Titanium Alloys at Temperatures up to 600°C - Wear of Materials 1985, American Society of Mechanical Engineers, 1985, p 370-426.
6. Анализ и исследование причин недостаточной износостойкости деталей приводящие к отказам систем и агрегатов АТ, а также преждевременной замене изношенных деталей. Отчет по НИР 499В-84, КИИГА, руков. Алябьев А.Я., ДР.01.84.005798. – К.: КИИГА 1984. – 75 с.
7. K.J. Kubiak, T.G. Mathia, S.Fouvry. Interface roughness effect on friction map under fretting contact conditions - Tribology International, Vol. 43, Issues 8 (2010) p. 1500-1507.
8. D. Aldham, J. Warburton, and R.E. Pendlebury. The Unlubricated Fretting of Mild Steel in Air - Wear, Vol 106, 1985, p. 177-201.
9. Гольдфайн В.Н., Зуев А.М., Каблуков А.Г. Проблемы трения и изнашивания – Киев, Техника – 1975, №. 8, – С. 35 – 41.
10. Зоткин В.Е. Методология выбора материалов и упрочняющих технологий в машиностроении: Материаловедение в машиностроении и Металловедение и термическая обработка металлов. – 3-е изд., перераб. и доп. / В.Е. Зоткин. – М.: Высш. шк., 2004. – 368 с.

11. Горынин И.В., Чечулин Б.Б. Титан в машиностроении. – М.: Машиностроение, 1990. – 400с.
12. Голего Н.Л., Алябьев А.Я., Шевеля В.В. Фреттинг-коррозия металлов. – К.: Техника, 1974. – 272с.
13. Шевеля В.В., Олександренко В.П. Трибохимия и реология износостойкости: Монография. – Хмельницкий: ХНУ, 2006. – 278с.
14. Васильєв О.І., Присяжнюк В.В. Дослідження впливу природи контактуючих матеріалів на зносостійкість вакуумних іонно-плазмових покриттів в умовах фретинг-корозії. // Проблеми тертя та зношування: Науково-технічний збірник. – К.: НАУ, 2006, – Вип. 45. – С.119-126.
15. Духота А.И. Обеспечение работоспособности титановых деталей в условиях фреттинг-коррозии. Автореф. дис. на соиск…канд. техн. наук спец. 05.02.04. – К.: КИИГА, 1982. – 24с.
16. Ляшенко Б.А., Рутковський А.В., Міриненко В.І., Петренко А.М. Гідрообразивна стійкість титанового сплаву ВТ-20 з вакуум-плазмовими покриттями. // Проблеми трибології. – 2004, №2. – С.142–148.
17. Масленков С.Б., Масленкова Е.А. Стали для высоких температур / Справочник в 2-х кн. Кн. 2 – М.: Металлургия, 1991. – С.583–586.
18. Физико-химические свойства окислов. Самсонов Г.В., Борисова А.Л., Жидкова Т.Г. и др. / Справочник. – М.: Металлургия, 1978. – 472с.
19. Технологическая инструкция по применению покрытий при ремонте деталей авиационной техники, поврежденных фреттинг-коррозией. – М.: Воздушный транспорт, 1980, – с.75.
20. S.F. Calhoun. Effects of Metal Hardness and Surface Finish upon Friction Wear. - Technical Report No. 63-1835, Rock Island Arsenal, 28 May 1963.
21. J.C. Gregory. A Salt Bath Treatment to Improve the Resistance of Ferrous Metals to Scuffing, Wear, Fretting, and Fatigue - Wear, Vol 9, 1966, p 249-281.
22. Патент 62-74065 Япония, МКИ С 23 С 8/24. Трущийся материал из титана / Футамура Кэнъитиро (Япония); Тайхо коге к.к. – №60-213638; Заявл. 28.09.85; Опубл. 04.04.87. – 3 с.

23. Сыропятов В.Я., Зинченко В. М., Барелко В. В. Каталитическое азотирование как путь снижения температуры поверхностного упрочнения титана и его сплавов // Труды 4 Собр. металловедов России. – Ч. 1.– Пенза.– 1998. – С. 91-93.
24. D. Godfrey and E.E. Bisson. Bonding of Molybdenum Disulphide to Various Materials to Form a Solid Lubricating Film, Pt. II. Friction and Endurance Characteristics of Films Bonded by Practical Methods - Technical Note No. 2802, NACA, 1952.
25. Улиг Г.Г., Реви Р.У. Коррозия и борьба с ней. Введение в коррозионную науку и технику: Пер.с англ./Под ред. А.М. Сухотина.-Л.: Химия, 1989. – пер. изд., США, 1985. – 456 с.: ил.
26. Анализ типовых соединений авиационных конструкций, у которых возможно разрушение от усталости вследствие развития фреттинг-коррозии в процессе эксплуатации, с целью установления путей повышения их срока службы. Отчет по НИР 187В-73, руков. Алябьев А.Я. ДР.73016615, – К.: КИИГА 1975. – 151 с.
27. Mansot, J. L., Bercion, Y., Romana, L., Martin, J. M. Nanolubrication. - Brazilian Journal of Physics, vol. 39, Issue 1A, p.186-197.
28. ExxonMobil Global Services Company. Technical topics URL. – Access mode: http://www.mobilindustrial.com
29. Солонина О.П., Глазунов С.Г. Жаропрочные титановые сплавы – М.: Металлургия 1979. – 448 с.
30. H. Nisitani, T. Umeno, H. HigakiNisitani, H., Umeno, T., Higaki, H. Effect of roughness on the frictional behavior between spheres (SUJ2) and plane (0.45% carbon steel) - DAMAGE AND FRACTURE MECHANICS - INTERNATIONAL CONFE, Vol.7 No., 2003, Japan.
31. Провести исследование, разработать и внедрить технологическую инструкцию по восстановлению деталей из титановых сплавов методом газотермического напыления. Отчет о НИР № 1.01.06.119, руков. Н.Ф. Григорьев. – Москва 1987. – 80 с.Комков О. Ю.

32. Орехова В. В., Байрачный Б. И. Теоретические основы гальваностегических процессов. К.: Выща шк., 1988. – 208 с.
33. В. Н. Надтока. Вакуумные дуговые источники радиальных потоков плазмы. // Сб. докл. Харьковской научной ассамблеи ICVTE-6. Харьков. 2003, с. 259-261.
34. Словарь справочник по трению, изнашиванию и смазке деталей машин /В.Д. Зозуля, Д.Я. Ровинский и др.; АН УССР Ин-т проблем материаловедении. – 2 изд. перер. и доп. – К. Наук. думка, 1990. – 264 с.
35. С. Я. Грилихес Обезжиривание, травление и полирование металлов. Издательство Машиностроение. Л. 1983 г. 101 с.
36. А.А. Андреев, В. Г. Василина, В. И. Зайцев, Г. Н. Картмазов, В.Н. Надтока, И. М. Неклюдов, Л. П. Саблев, Р. И. Ступак. «Устройство для ионно-плазменного нанесения покрытий на внутреннюю поверхность труб» - Пат. Украины № 76344, 01.11.04, опубл. 17.07.2006, Бюл. № 7.
37. НПАОП 63.23-1.02-08 Правила безпеки праці під час обслуговування спецтранспорту та засобів механізації в аеропортах цивільної авіації. - Держгірпромнагляд України, 2008.
38. Закон України про охорону навколишнього середовища від 26.06.91.
39. С.С. Виноградов. Экологически безопасное гальваническое производство. – М.: Глобус, 1998. – 302 с.
40. Ю.П. Хранилов. Экология и гальванотехника.: учеб.пособие.- Киров: ВятГТУ, 2000.- 97 с.
41. НПАОП 62.0-7.13-78-ОСТ 54 72001-78 Шум. Общие требования безопасности труда в эксплуатационных предприятиях гражданской авиации. - Министерство гражданской авиации от 14.06.78 № 72/1—599.
42. НПАОП 62.0-3.01-08 Норми безплатної видачі спеціального одягу, спеціального взуття та інших засобів індивідуального захисту працівникам авіаційного транспорту. –Держгірпромнагляд України від 25.03.2008 № 57.

43. НПАОП 63.23-1.06-98 Правила безпеки праці при технічному обслуговуванні і поточному ремонті авіаційної техніки. - Держнаглядохоронпраці України - 18.05.1998. Наказ № 92.
44. ГОСТ 12.0.003-74 ССБТ Система стандартов безопасности труда. Опасные и вредные производственные факторы. Классификация. - М.: Изд-во стандартов, 1976.
45. Green JE. Civil aviation and the environmental challenge. – Aeronautical Journal 107: 281-99, 2003.
46. СНиП 21-01-97 Пожарная безопасность зданий и сооружений. - Минстрой России, 1997.
47. Christian N. Jardine. Calculating the Environmental Impact of Aviation Emissions. - Oxford: University of Oxford, 2005.
48. ДСанПіН 3.3.2-007-98 Державні санітарні правила і норми роботи з візуальними дисплейними терміналами електронно-обчислювальних машин ЕОМ. - МОЗ України. Державний санітарний лікар України Постанова №7 10.12.98.