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.
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«_____»_____________2022 р.

КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ЗДОБУВАЧА ОСВІТНЬОГО СТУПЕНЯ
«МАГІСТР»

ЗА ОСВІТНЬО-ПРОФЕСІЙНОЮ ПРОГРАМОЮ
«ТЕХНІЧНЕ ОБСЛУГОВУВАННЯ ТА РЕМОНТ ПОВІТРЯНИХ СУДЕН І АВІАДВИГУНІВ»

Тема: «Підвищення зносостійкості деталей авіаційної техніки газотермічними покриттями»

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Київ 2022

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
«____”_______________ 2022

MASTER’S DEGREE THESIS

(EXPLANATORY NOTE)

GRADUATE OF EDUCATIONAL DEGREE

«MASTER»

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

Topic: «Improving of wear resistance of aeronautical equipment parts by gas-thermal coatings»

Created by: ___________ **A.A. Zadniprianyi**

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Pd. D., Assoc. Professor _____________ **L.I. Pavlyukh**

Standards Inspector: _____________

Kyiv 2022

NATIONAL AVIATION UNIVERSITY

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

APPROVED BY
Head of Department
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«____» ____2022 year

Graduate Student's Degree Work Assignment

ZADNIPRIANYI ARTEM

1. The topic of the work: **«Improving of wear resistance of aeronautical equipment parts by gas-thermal coatings»** approved by the Rector's order of September 29, 2022 No. 1786/st.
2. The work fulfillment terms: from September 26, 2022 till November 30, 2022.
3. Initial data for the project (thesis): analysis of the damage of titanium alloys details and durability of refurbished details by means of thermal spraying aircraft parts.
4. The content of the explanatory note: analysis of damage to components of aircraft due to wear, application of coatings in aviation, analysis of methods for repairing parts in aviation, conducting experiments, processing of experimental results, analysis of safety and environmental protection.
5. The list of mandatory graphic materials: Theme; List of tasks; methods of aviation components repair; implementation of sprayed coatings; fretting problem; analysis of methodologies on conducting tests; МФК-1 installation; wear measurement; wear resistance results; friction surfaces fractography; surface topography; conclusions and recommendations.

6. Calendar schedule

Task	Fulfillment term	Completion mark
Literature review of materials for degree work	26.09.22 – 28.09.22	
Analysis of technological process of work fulfillment	29.09.22 – 10.10.22	
Preparation of necessary equipment for research carrying out	11.10.22 – 16.10.22	
Work on a special part of degree work	17.10. 22 – 25.10. 22	
Processing of research results	26.10. 22 – 30.10. 22	
Fulfillment of individual sections of degree work	01.11. 22 – 03.11. 22	
Processing of master’s degree work	04.11. 22 – 25.11. 22	

7. Advisers on individual sections

Section	Adviser	Date, Signature	
		Assignment Delivered	Assignment Accepted
Labour precaution	Ph. D., Assoc. Prof. K.I. Kazhan		
Environmental protection	Ph. D., Assoc. Prof. Pavlyukh L.I.		

8. Assignment issue date «_____»___________ 2022.

Degree work supervisor: ___________________ A.M. Khimko
(signature)

Assignment accepted for fulfillment ____________________ A.A. Zadniprianyi
(signature)

ABSTRACT

Explanatory note to diploma project **Improving of wear resistance of aeronautical equipment parts by gas-thermal coatings** is written at

80 pages has 29 pictures and 9 tables, used literature includes 38 references.

The aim of the thesis was definition of wear resistant of refurbished titanium alloys by means of thermal spraying and choosing of the most wear resistant coating.

Object of research are fretting processes of sprayed coatings in couple with alloy steel.

Subject of research are damages of sprayed coatings in result of fretting.

Methodology of research includes laboratory tests of sprayed coatings, fractographical research of surfaces friction traces, optical and electronic analysis of achieved results.

Diploma project gives straight understanding of processes of sprayed coatings fretting destruction.

Materials of that diploma project is advised to be used during studying process and at the specialists practical activity

SPRAYED COATINGS, PLASMA SPRAYING, FRETTING, MOLYBDENUM, ВТ-22, ПС12НВК-01, ВКНА, ПГ10Н.

LIST OF ABBREVIATIONS

PTWA - plasma transferred wire arc

HVOF - high velocity oxygen fuel

SPPS – solution precursor plasma spray

TBC – thermal barrier coatings

USZ – ultra-stabilized zirconia

CMC– ceramic-matrix composites

EBPVD – electron beam physical vapor deposition

APS – air plasma spray

ESAVD – electrostatic spray assisted vapour deposition

CAA – clean air act

RCRA – resources conservation and recovery act

NAAQS– national ambient air quality standards

MACT – maximum achievable control technology

HEPA – high-efficiency particle absorption

BACT – best available control technology

CONTENTS

INTRODUCTION

Today almost all fields of engineering, manufacturing building constructions, energy, engine, aerospace, as well as in other areas of new technology widely use thermal coatings. With coatings we can solve many problems, increase of weather resistance, operational stability, adhesion, thermal stability, erosion resistance, protective properties and chemical resistance for calendar resource. But the most important problem is to increase the wear resistance of parts, assemblies of machines.

Application of protective wear-resistant coatings - is one of the most effective means of struggling with fretting wear. Currently, developed and used number of technological methods and a large range of materials that allow to obtain coatings with high wear resistance. In the production and repair of aviation equipment parts as wear-resistant coatings, the most widely used coating derived by gas-thermal spraying methods.

One of the areas in the protective coating is by plasma spraying. With high performance spraying, this technological method allows to deposit coatings with a wide range of characteristics, and apply them to restore dimensions of worn parts.

Implementation of the hot-gas methods of applying protective coatings only effective when properly choosing the material and its properties matching technological capabilities specific spraying techniques. However, information about the properties of powders produced, for lack of wear-resistant coatings and existing construction incomplete and contradictory.

Given the fact that the concept of "durability" - is complex, the final conclusion on efficiency gas-thermal coatings can only be given by special tribotechnical test facilities simulating real friction in certain modes.

PART 1 WEARING PROCESSES IN AVIATION

1.1 Surface wear

Adhesive wear

Engineering surface is never perfectly flat. The surface of a most highly polished engineering component show irregularities or asperities. When two such surfaces are brought into contact, the real contact actually occurs only at some high asperities which is a small fraction, e.g. 1/100 of the apparent contacting area. As a result, plastic deformation and intermetallic adhesion will occur, forming cold weld junctions between the contacting asperities. The strength of junction is determined by the surface structure and by the mutual solubility of two contact metals. The tendency of adhesion is the lowest for a pair of metals with almost zero mutual solubility, but this is limited to very few metals. Most metallic materials show appreciable tendency of adhesion (Figure 1.1).

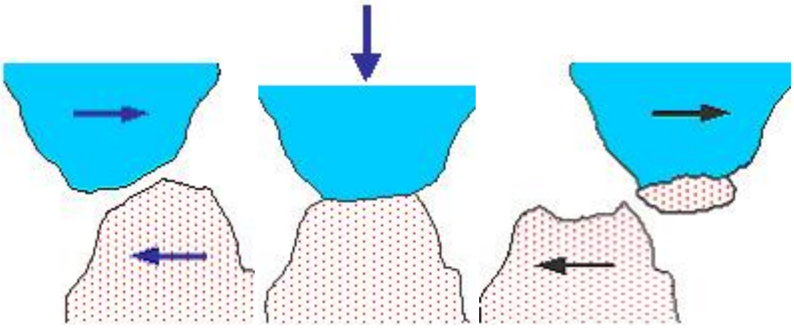


Figure 1.1 – Adhesive wear occurs by material transfer

When two contact surfaces undergo relative movement, tearing must take place either at the (cold weld) junction or inside the original materials depending on which is weaker. If the strength of the adhesion junction is relatively low, as in the case of a contact pairs with low mutual solubility, or metallic surfaces separated by oxide film, tearing will take place at the junction and material loss during wear will be minimal. However, when tearing occurs inside the softer material, a fragment of the softer material will be dragged away and adhering to the harder body, as a schematic shown in Figure 1.2. This process is known as material transfer [1].

The transferred fragment is plastically deformed during continued action of sliding so that the transferred materials frequently has a plate-like morphology. Multi-material transfer and plastic deformation of the transferred material result in a layered surface morphology on the counterface as shown in Fig. 4. The next stage is detachment of the transferred layer, probably when the bond between the layer and the underlying material has been locally weakened by cyclic loading.

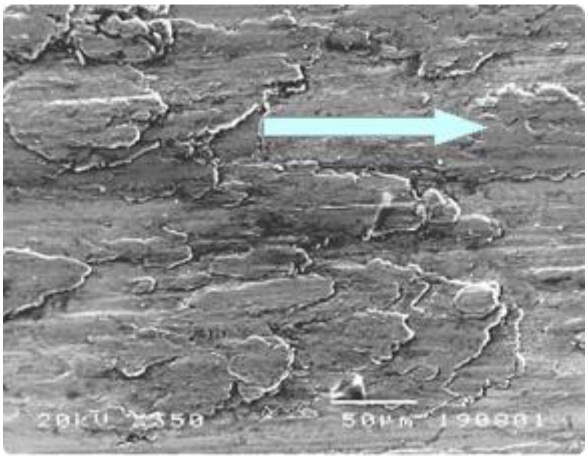


Figure 1.2 – Transferred layers of titanium alloy on a steel surface

Prediction of wear rate.

Adhesive wear is dominated by material transfer and removal of the transferred material. The former is determined by the material properties and the strength of adhesion junction while the latter by the sliding conditions. Archard proposed that adhesive wear rate, W, can be expressed by the following equation

$$W = K\frac{P}{H} \tag{1.1}$$

where: P is the applied normal load,

H is the hardness of the softer material of the two contact bodies,

K is referred to as wear coefficient.

Coefficient K is related to the possibility of generation of wear debris from each contact. K would be higher if two contacting materials have higher mutual solubility. K would also be higher when wear occurs in a vacuum or an inert atmosphere, such that adhesive wear is one of the major problems for contacting components, e.g. bearing, in a spacecraft or satellite.

How to improve adhesive wear resistance.

– Improving mechanical properties (hardness and strength) of the contacting material because tearing is more likely to happen in adhesion junction.

– Material selection or changing the chemical nature of the surfaces, e.g. by surface engineering, will fundamentally reduces the possibilities of adhesion and reduce adhesive wear rate.

A tailored surface engineering process will increase the surface hardness of a contacting surface, and reduce the possibility of adhesion between contacting surfaces, therefore, **surface engineering** is the most effect way to improve the adhesive wear resistance.

Abrasive wear

Abrasive wear (wear by abrasion) is the most frequently encountered wear mechanism in industry. There are two types of situation where abrasive wear may occur.

– The first is referred to as **three-body abrasion** which involves foreign hard particles, either trapped between two sliding surfaces and abrading one or both surfaces, or embedded in a softer surface and abrading the opposing one. Examples of three body abrasion can readily be found in mining industry and in machines working in desert (Figure1.3).

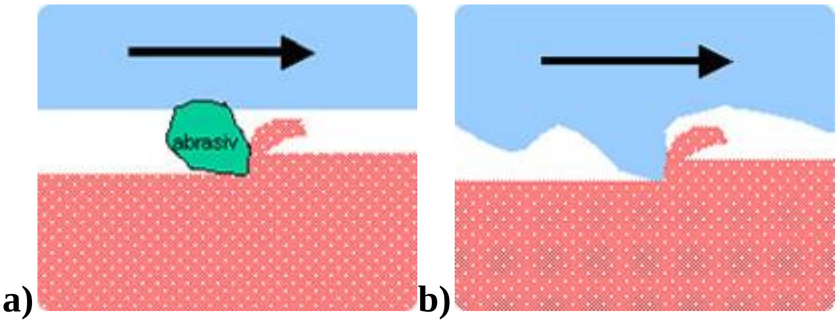


Figure1.3 – a) three body abrasion and b) two body abrasion

– The second type of abrasive wear is named as **two-body abrasion** which occurs in metal-on-metal contact when the protuberances (asperities) on a hard surface plough or cut through the other surface. Since asperities exist in every engineering surface and they never can be eliminated even by very sophisticated polishing, thus, the possibility of two-body abrasion will always exist. Frequently, two-body and three-body abrasions are combined in service as an application that was originally metal against metal (two-body) may evolve into three body abrasion, such as the generation of work hardened wear debris or the introduction of abrasive particles through contaminated lubricant (Figure 1.4).

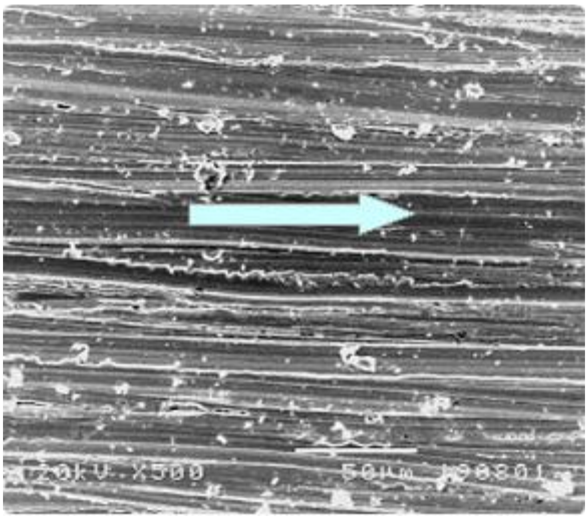


Figure 1.4 – Steel surface worn by abrasion

Mechanism of abrasive wear.

The mechanism of material removal in abrasive wear is basically the same as machining and grinding during a manufacturing process.

At the onset of wear, the hard asperities or particles penetrate into the softer surface under the normal contact pressure. When a tangential motion is imposed, the materials in the softer surface is removed by combined effects of 'micro-ploughing', 'micro-cutting' and 'micro-cracking'. As a result, the worn surface is generally characterised by grooves and scratches as an example shown in Figure 1.4. The wear debris often has a form of micro-cutting chips [2].

Prediction of abrasive wear rate.

Several models have been proposed to predict the volume loss in abrasive wear. A simplest one involves the scratching of materials by a conical hard particle (indenter). Under a applied load of P, the hard particle penetrates the material surface to a depth of h which is linearly proportional to the applied load (P) and inversely proportional to the hardness (H) of the surface being abraded. As sliding occurs, the particle will plough (cut) the surface producing a groove, with the material originally in the groove being removed as wear debris. If the sliding distance is L, the wear volume (V) can be expressed as:

$$V = k \cdot \frac{PL}{H} \tag{1.2}$$

where: P – load,

H – hardness,

V – wear volume,

In which, k is wear coefficient partly reflecting the influences of geometries and properties of the particles (or asperities), and partly reflecting the influences of many other factors such as sliding speed and lubrication conditions.

How to improve abrasive wear resistance.

Equation indicates that wear loss can be reduced by

– decreasing contact load,

– reducing sliding distance,

– reducing k value by eliminating the presence of hard particles and reducing surface roughness of the counterface.

However, these changes are frequently impossible in practice if the function of a machine is to be maintained. Then, increasing hardness (H) by means of material selection, heat treatment and **surface engineering** will be the most effective and relatively easy way to solve an abrasive wear problem.

Fretting

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.

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 [3].

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.

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:

1. The applied normal load causes asperities to adhere, and the tangential oscillatory motion shears the asperities and generates wear debris that accumulates.
2. 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.
3. Once the particles have accumulated sufficiently to span the gap between the surfaces, abrasion wear occurs and the wear zone spreads laterally.
4. As adhesion, delamination and abrasion wear continue, wear debris can no longer be contained in the initial zone and it escapes into surrounding valleys.
5. 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.

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 [4].

Very little wear occurs at amplitudes below 100 micrometers as shown in Figure 1.5-1.6.

At slips below 100 micrometers, nucleation and propagation of cracks that lead to wear debris are too minute to be detected. The wear debris rolling at that degree of oscillation presumably causes this low wear rate. At high amplitudes, direct abrasion of the interface by hard particles (oxide or work-hardened particles) creates the gross wear rate. At large amplitudes of oscillation, the fretting wear coefficient is approximately the same as that of unidirectional wear.

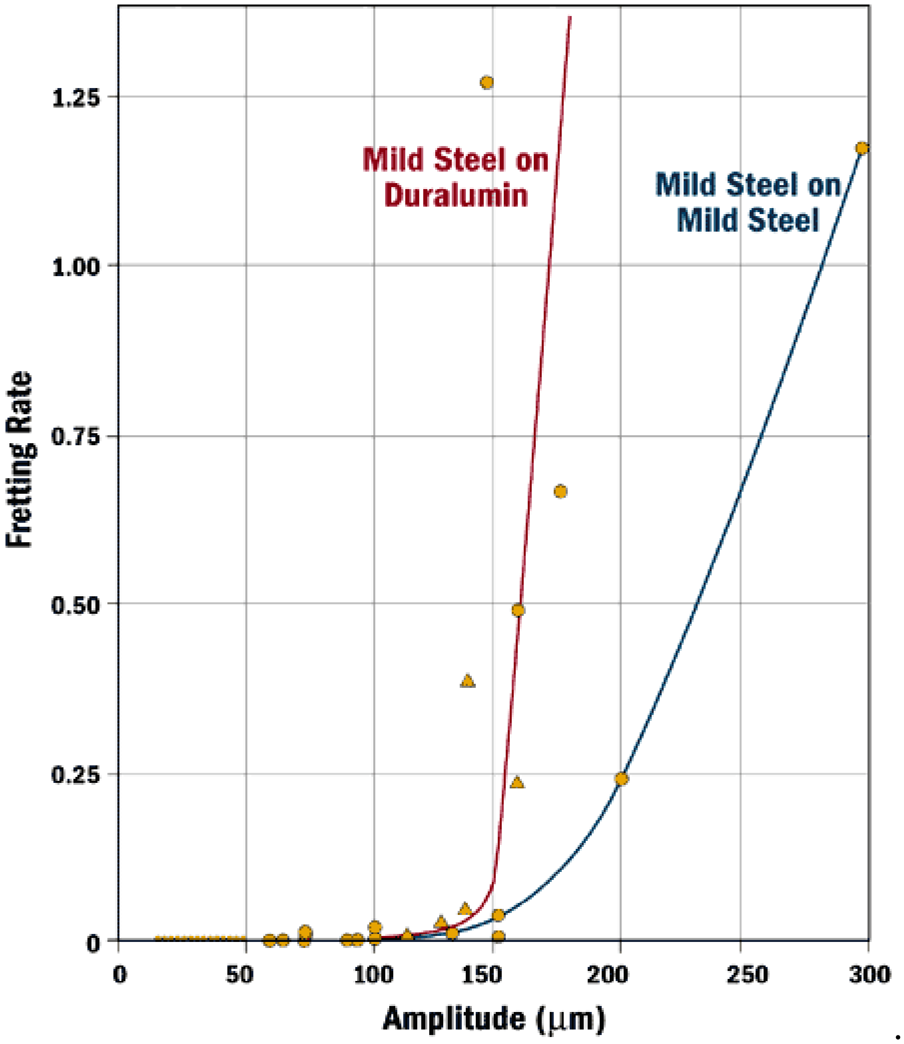


Figure 1.5 – Fretting Wear vs. Slip Amplitude

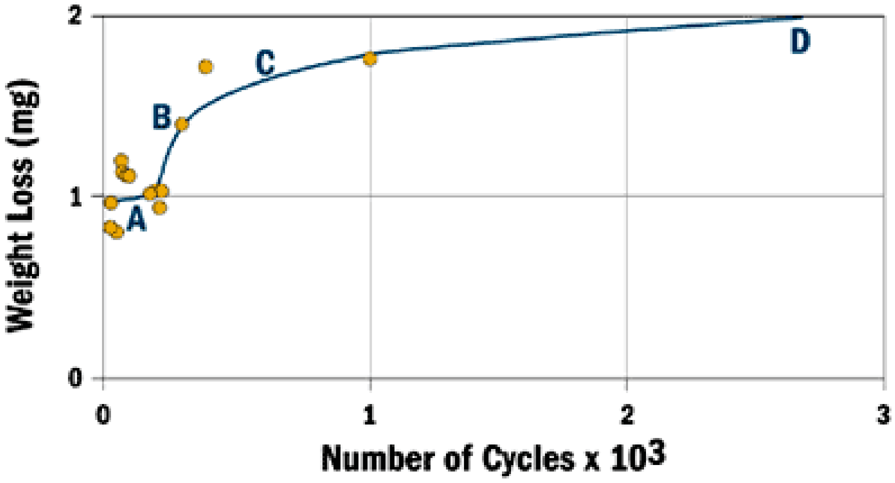


Figure 1.6 – Fretting Wear vs. Running Time

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 1.7-1.8. shows:

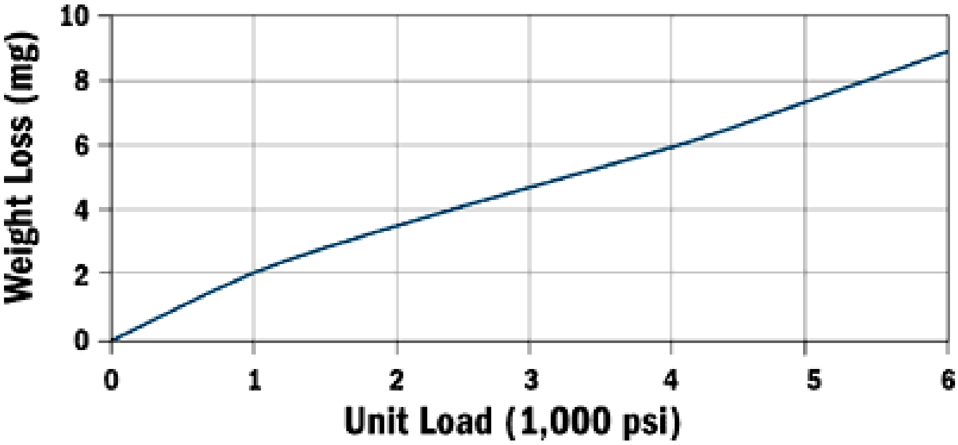


Figure 1.7 – Fretting Wear vs. Normal Unit Load

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.

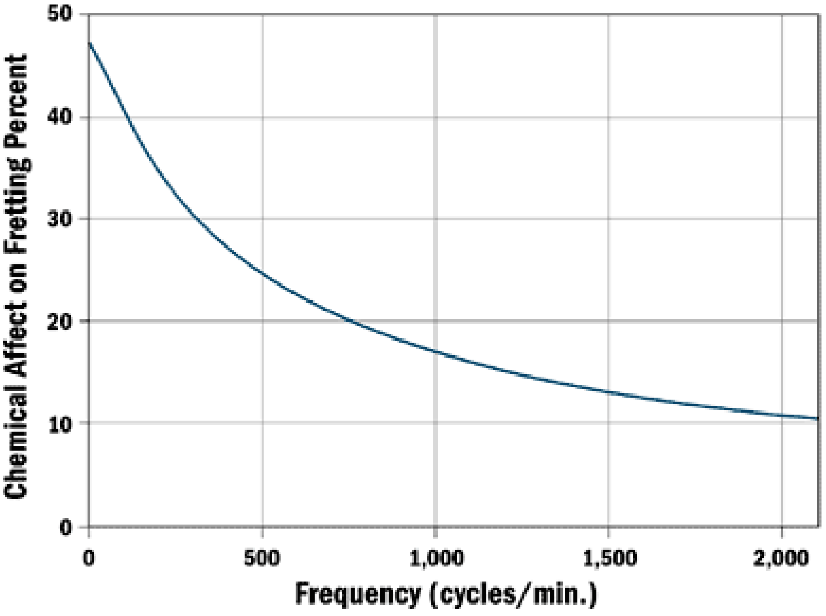


Figure 1.8 – Effect of Frequency on Fretting Damage of Mild Steel Fretting

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.

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. 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.

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.”

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.

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.

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 [5].

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.

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.

1.2 Surface recovering

Cladding.

Reconstructive cladding is used to obtain the original dimensions of worn or damaged parts. In this case, the weld metal is similar in composition and mechanical properties of the base metal.

The most important requirements for surfacing, are as follows:

1. Minimum penetration of the base metal;
2. Minimum agitation of the deposited layer with the base metal;
3. The minimum value of residual stresses and strains in the area of metal cladding;
4. Understatement to acceptable values allowances for subsequent processing details.

Manual arc cladding (welding).

Manual arc welding is used to restore worn surfaces, eliminating damage casting and receiving surfaces with special properties.

To perform welding using coated melt; Carbon and graphite electrodes. The most widely used are the electrodes UONI-13/50, -13/60, -13/80 with fluorine-coated calcium. Surfacing operate on DC reverse polarity. In compliance regimes surfacing specified in the passport to the electrodes, achieved sufficient density and fineness of the metal and weld cracking excluded.

Automatic welding in shielding gases.

Automatic welding in shielding gases used in cases where the impossible or difficult welding submerged. To protect the arc zone and the molten metal using carbon dioxide, argon or mixtures thereof, sometimes supplemented with oxygen.

Plasma cladding.

Plasma cladding is performed using a granular or powdered materials of wire, high-alloy steels. Plasma surfacing has broad technological capabilities: the thickness of the deposited layer in a single pass can be varied from 0.25 to 9.5 mm and width – from 1.2 to 45 mm.

Vibro-arc cladding.

Vibro-arc cladding lies in the fact that between the electrode and the surfaced surface periodically excited and extinguished arc. At short-circuit, the molten metal is welded to the wire surface. To reduce the heating water emulsion product is cooled (50...60 g of soda and 10...15 g of the crude soap in 1 liter of water). Deposition is done in the following mode: power supply - 14...24; core wire diameter - 1,6...2,5 mm; welding current - 100...250 A; the oscillation frequency of the electrode - 25...100 Hz.

During surfacing product and rotates wire electrode moves along a generatrix and simultaneously performs reciprocating motion. vibroarc surfacing restore the surface of steel and iron products. Per pass is fused layer thickness up to 3 mm.

Electro slag surfacing.

Electro slag surfacing subjected to flat and cylindrical surfaces. It can be recommended for products whose surface layers should be uniform in thickness and have a defined chemical composition.

Laser cladding.

Laser cladding is a method of depositing material by which a powdered or wire feedstock material is melted and consolidated by use of a laser in order to coat part of a substrate or fabricate a near-net shape part (additive manufacturing technology). It is often used to improve mechanical properties or increase corrosion resistance, repair worn out parts, and fabricate metal matrix composites (Figure 1.9).

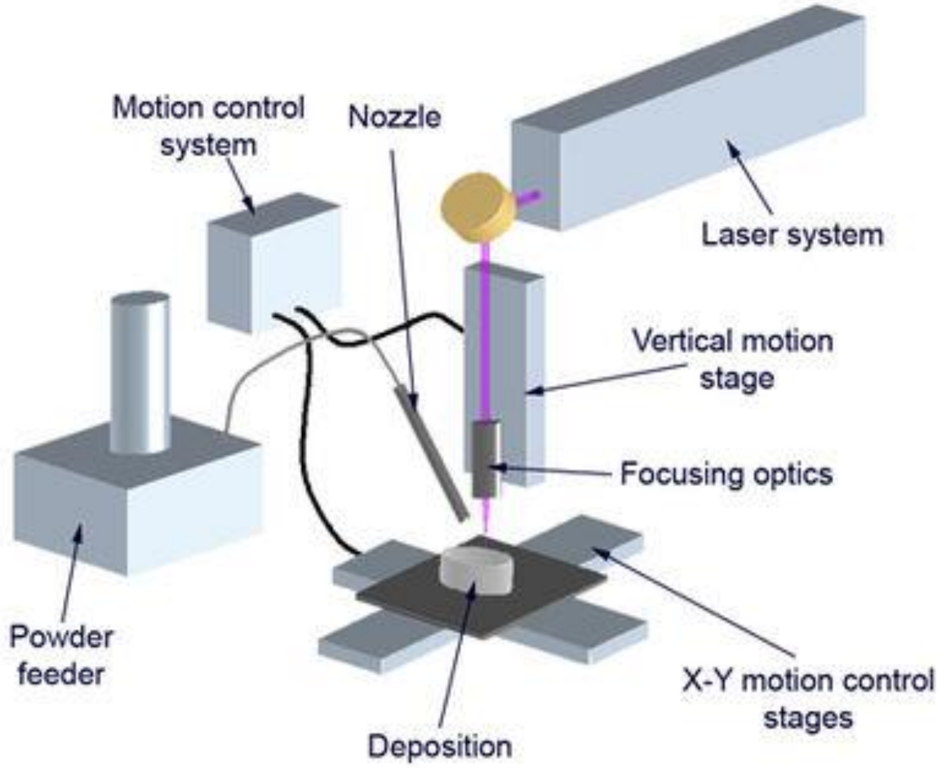


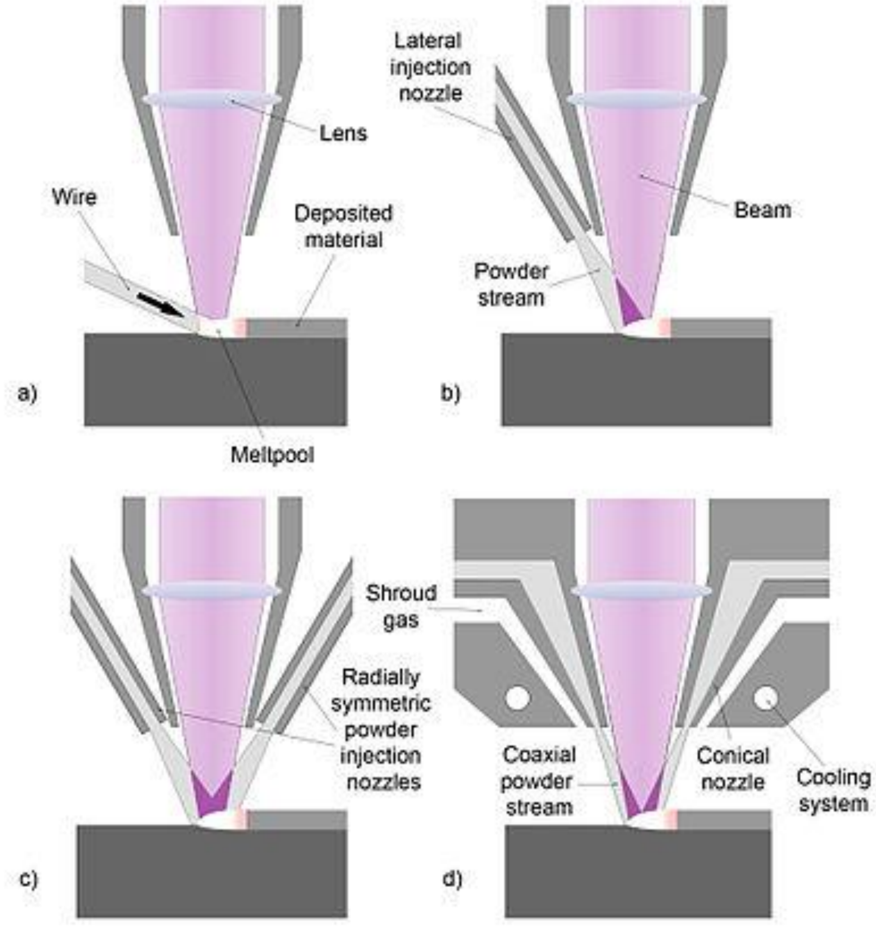
Figure 1.9 – A schematic of the equipment

Process.

The powder used in laser cladding is normally of a metallic nature, and is injected into the system by either coaxial or lateral nozzles. The interaction of the metallic powder stream and the laser causes melting to occur, and is known as the melt pool. This is deposited onto a substrate; moving the substrate allows the melt pool to solidify and thus produces a track of solid metal. This is the most common technique, however some processes involve moving the laser nozzle assembly over a stationary substrate to produce solidified tracks. The motion of the substrate is guided by system which interpolates solid objects into a set of tracks, thus producing the desired part at the end of the trajectory [6].

A great deal of research is now being concentrated on developing automatic laser cladding machines. Many of the process parameters must be manually set, such as laser power, laser focal point, substrate velocity, powder injection rate, etc., and thus require the attention of a specialized technician to ensure proper results. However, many groups are focusing their attention on developing sensors to measure the process online.

Such sensors monitor the clad's geometry (height and width of deposited track), metallurgical properties (such as the rate of solidification, and hence the final microstructure), and temperature information of both the immediate melt pool and its surrounding areas. With such sensors, control strategies are being designed such that constant observation from a technician is no longer required to produce a final product. Further research has been directed to forward processing where system parameters are developed around specific metallurgical properties for user defined applications (such as microstructure, internal stresses, delusion zone gradients, and clad contact angle).



a) – wire surfacing, b) – powder surfacing, c) – dual nozzle powder surfacing,
d) – arc surfacing.

Figure 1.10 – The different feeding systems available

Advantages.

- Best technique for coating any shape => increase life-time of wearing parts.
- Particular dispositions for repairing parts (ideal if the mould of the part no longer exist or too long time needed for a new fabrication).
- Most suited technique for graded material application.
- Well adapted for near-net-shape manufacturing.
- Low dilution between track and substrate (unlike other welding processes and strong metallurgical bond.
- Low deformation of the substrate and small heat affected zone.
- High cooling rate => fine microstructure.
- A lot of material flexibility (metal, ceramic, even polymer).
- Built part is free of crack and porosity.
- Compact technology.

Thermal spraying.

Thermal spraying techniques are coating processes in which melted (or heated) materials are sprayed onto a surface. The "feedstock" (coating precursor) is heated by electrical (plasma or arc) or chemical means (combustion flame).

Thermal spraying can provide thick coatings (approx. thickness range is 20 micrometers to several mm, depending on the process and feedstock), over a large area at high deposition rate as compared to other coating processes such as electroplating, physical and chemical vapor deposition. Coating materials available for thermal spraying include metals, alloys, ceramics, plastics and composites. They are fed in powder or wire form, heated to a molten or semi molten state and accelerated towards substrates in the form of micrometer-size particles. Combustion or electrical arc discharge is usually used as the source of energy for thermal spraying. Resulting coatings are made by the accumulation of numerous sprayed particles. The surface may not heat up significantly, allowing the coating of flammable substances [7].

Coating quality is usually assessed by measuring its porosity, oxide content, macro and micro-hardness, bond strength and surface roughness. Generally, the coating quality increases with increasing particle velocities.

Plasma spraying.

In plasma spraying process, the material to be deposited (feedstock) - typically as a powder, sometimes as a liquid, suspensionor wire - is introduced into the plasma jet, emanating from a plasma torch. In the jet, where the temperature is on the order of 10,000 K, the material is melted and propelled towards a substrate. There, the molten droplets flatten, rapidly solidify and form a deposit. Commonly, the deposits remain adherent to the substrate as coatings; free-standing parts can also be produced by removing the substrate. There are a large number of technological parameters that influence the interaction of the particles with the plasma jet and the substrate and therefore the deposit properties. These parameters include feedstock type, plasma gas composition and flow rate, energy input, torch offset distance, substrate cooling, etc.

Wire arc spray.

Wire arc spray is a form of thermal spraying where two consumable metal wires are fed independently into the spray gun. These wires are then charged and an arc is generated between them. The heat from this arc melts the incoming wire, which is then entrained in air jet from the gun. This entrained molten feedstock is then deposited onto a substrate. This process is commonly used for metallic, heavy coatings [8].

Cold Spraying (Gas dynamic cold spray).

Gas dynamic cold spray is a coating deposition method developed in the mid-1980s in the Soviet Union in The Institute of Theoretical and Applied Mechanics by Papyrin and his team. The solid powders (1 to 50 micrometers in diameter) are accelerated in supersonic gas jets to velocities up to 500–1000 m/s. During impact with the substrate, particles undergo plastic deformation and adhere to the surface. To achieve a uniform thickness the spraying nozzle is scanned along the substrate. Metals, polymers, ceramics, composite materials and nanocrystalline powders can be deposited using cold spraying. The kinetic energy of the particles, supplied by the expansion of the gas, is converted to plastic deformation energy during bonding. Unlike thermal spraying techniques e.g., plasma spraying, arc spraying, flame spraying, high velocity oxygen fuel the powders are not melted during the spraying process.

To date, there are two main types of gas dynamic cold spray.

1. High Pressure Cold Spray. The working gas is nitrogen or helium at pressures above 1.5 MPa, flow rate of more than 2 m^3/min, heating power of 18 kW. For spraying are used a pure metal powders with the sizes of 5-50 μm

2. Low Pressure Cold Spray. The working gas is a compressed air with pressure 0.5-1.0 MPa, flow rate 0.5–2 m^3/min and the heating power 3-5 kW. For spraying are used a mechanical mixture of metal and ceramic powders. The inclusion of a ceramic component in the mixture provides high-quality coatings with relatively low energy consumption (Figure 1.11).

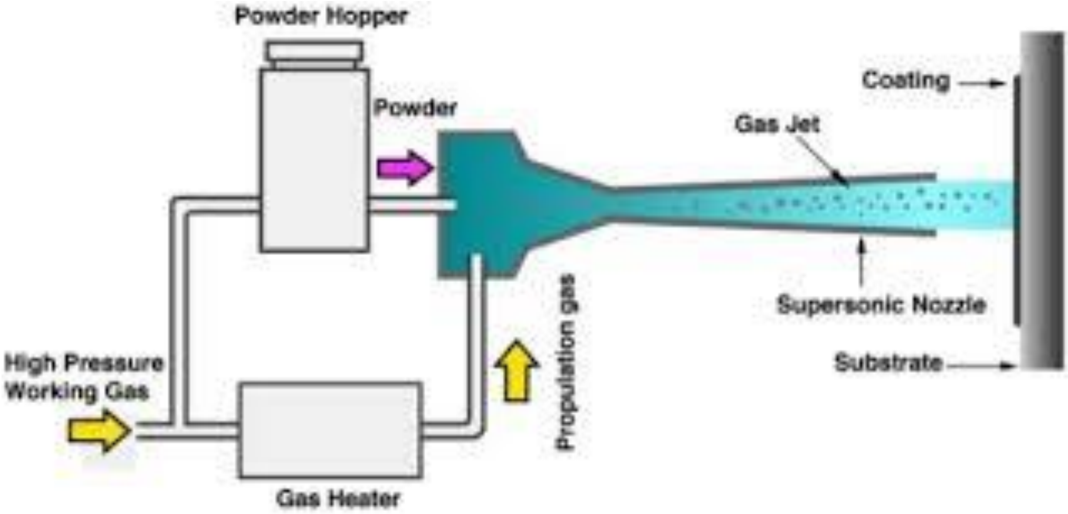


Figure 1.11 – A schematic of the equipment

The most prevailing bonding theory in cold spraying is attributed to "adiabatic shear instability" which occurs at the particle substrate interface at or beyond a certain velocity called critical velocity. When a spherical particle travelling at critical velocity impacts a substrate, a strong pressure field propagates spherically into the particle and substrate from the point of contact. As a result of this pressure field, a shear load is generated which accelerates the material laterally and causes localized shear straining. The shear loading under critical conditions leads to adiabatic shear instability where thermal softening is locally dominant over work strain and strain rate hardening, which leads to a discontinuous jump in strain and temperature and breakdown of flow stresses. This adiabatic shear instability phenomena results in viscous flow of material at an outward flowing direction with temperatures close to melting temperature of the material. This material jetting is also a known phenomenon in explosive welding of materials.

Cold spray is now used to repair machine parts in a matter of minutes. Metal (nickel alloys) particles travel in a blend of nitrogen and helium gas and gradually stack up on the damaged part to recreate the desired surface. A robot controls the movement of the sprayer. The U.S. Army uses the technology to repair a component in Blackhawk helicopters. General Electric is adapting the technology for civilian applications.

Plasma transferred wire arc (PTWA) thermal spraying is a thermal spraying process that deposits a coating on the internal surface of a cylindrical surface, or external surface of any geometry. It is predominantly known for its use in coating the cylinder bores of an engine, enabling the use of aluminum engine blocks without the need for heavy iron sleeves. A single conductive wire is used as "feedstock" for the system. A supersonic plasma jet melts the wire, atomizes it and propels it onto the substrate. The plasma jet is formed by a transferred arc between a non-consumable cathode and the wire. After atomization, forced gas transports the stream of molten droplets onto the bore wall. The particles flatten when they impinge on the surface of the substrate, due to their high kinetic energy. The particles rapidly solidify upon contact and can form both crystalline and amorphus phases. There is also the possibility to produce multi-layer coatings. The stacked particles make up a highly wear-resistant coating. All conductive wires up to and including 0.0625" (1.6 mm) can be used as feedstock material, including "cored" wires. PTWA can be used to apply a coating to the wear surface of engine or transmission components to replace a bushing or bearing. For example, using PTWA to coat the bearing surface of a connecting rod offers a number of benefits including reductions in weight, cost, friction potential, and stress in the connecting rod.

The inventors of PTWA received the 2009 IPO National Inventor of the Year award. This technology was initially patented and developed by inventors by Flame-

Spray Industries, Inc. The technology was subsequently improved upon by Ford and Flame-Spray Industries. PTWA is currently in use by Nissan in the Nissan GTR, Ford is implementing it in the new Mustang GT500 Shelby, Caterpillar and other manufacturers are using it for re-manufacturing.

Other applications for this process include the spraying of internal diameters of pipes. Any conductive wire can be used as the feedstock material, including "cored" wire.Refractory metals as well as low melt materials are easily deposited.

The recent use of PTWA by Nissan and Ford has been to apply a wear resistant coating on the internal surface of engine block cylinder bores. For hypoeutectic aluminum silicon alloy blocks, PTWA provides a great alternative to cast iron liners which are a higher cost and heavier. PTWA also delivers increased displacement in the same size engine package and a potential for better heat transfer.

Plasma transferred wire arc coatings are also applied directly to cast iron engine blocks for re-manufacturing. PTWA coated test engines have been run for over 3 million combined miles of trouble free on-the-road performance. The technology is currently in use at a number of major production facilities around the world. It is also being used to coat worn parts, to make them like-new in re-manufacturing facilities [9].

The High Velocity Oxygen Fuel Thermal Spray Process

The HVOF (High Velocity Oxygen Fuel) Thermal Spray Process is basically the same as the combustion powder spray process (LVOF) except that this process has been developed to produce extremely high spray velocity. There are a number of HVOF guns which use different methods to achieve high velocity spraying. One method is basically a high pressure water cooled HVOF combustion chamber and long nozzle. Fuel (kerosene, acetylene, propylene and hydrogen) and oxygen are fed into the chamber, combustion produces a hot high pressure flame which is forced down a nozzle increasing its velocity. Powder may be fed axially into the HVOF combustion chamber under high pressure or fed through the side of laval type nozzle where the pressure is lower. Another method uses a simpler system of a high pressure combustion nozzle and air cap. Fuel gas (propane, propylene or hydrogen) and oxygen are supplied at high pressure, combustion occurs outside the nozzle but within an air cap supplied with compressed air. The compressed air pinches and accelerates the flame and acts as a coolant for the HVOF gun. Powder is fed at high pressure axially from the centre of the nozzle.

The coatings produced by HVOF are similar to those produce by the detonation process. HVOF coatings are very dense, strong and show low residual tensile stress or in some cases compressive stress, which enable very much thicker coatings to be applied than previously possible with the other processes.

The very high kinetic energy of particles striking the substrate surface do not require the particles to be fully molten to form high quality HVOF coatings. This is certainly an advantage for the carbide cermet type coatings and is where this process really excels.

The HVOF coatings are used in applications requiring the highest density and strength not found in most other thermal spray processes. New applications, previously not suitable for thermal spray coatings are becoming viable.

Solution Precursor Plasma Spray (SPPS) is a thermal spray process where a feedstock solution is heated and then deposited onto a substrate. Basic properties of the process are fundamentally similar to other plasma spraying processes. However, instead of injecting a powder into the plasma plume, a liquid precursor is used. The benefits of utilizing the SPPS process include: the ability to create unique nanometer sized microstructures without the injection feed problems normally associated with powder systems and flexible, rapid exploration of novel precursor compositions [10].

The precursor solution is formulated by dissolving salts (commonly zirconium and yttrium when used to formulate thermal barrier coatings) in a solvent. Once dissolved, the solution is then injected via a pressurized feed system. As with other thermal spray processes, feedstock material is melted and then deposited onto a substrate. Typically, the SPPS process sees material injected into a plasma plume or High Velocity Oxygen Fuel (HVOF) combustion flame. Once the solution is injected, the droplets go through several chemical and physical changes and can arrive at the substrate in a several different states, from fully melted to unpyrolized. The deposition state can be manipulated through spray parameters and can be used to significantly control coating properties, such as density and strength.

Most current research on SPPS has examined is application to create thermal barrier coatings (TBCs). These complex ceramic/metallic material systems are used to protect components in hot sections of gas turbine and diesel engines. The SPPS process lends itself particularly well to the creation of these TBCs. Studies report the generation of coatings demonstrating superior durability and mechanical properties. Superior durability is imparted by the creation of controlled through thickness vertical cracks. These cracks only slightly increase coating conductivity while allowing for strain relief of stress generated by mismatch between the coating and the substrate during cyclic heating. The generation of these through thickness cracks was systematically explored and found to be caused by the depositing a controlled portion of unpyrolized material in the coating. Superior mechanical properties such as bond strength and in-plane toughness result from the nanometer sized microstructure that are created by the SPPS process.

Other studies have shown that engineered coatings can reduce thermal conductivity to some of the lowest reported values for TBCs. These low thermal conductivities were achieved through the generation of an alternating high-porosity, low-porosity microstructure or the synthesis of a low conductivity precursor composition with rare earth dopants.

1.3 Coating materials

Abradable Materials (clearance control coatings)

An abradable coating is a coating made of an abradable material – meaning if it rubs against a more abrasive material in motion, the former will be worn whereas the latter will face no wear.

Abradable coatings are used in aircraft jet engines in the compressor and turbine sections where a minimal clearance is needed between the blade tips and the casing.

In typical turbo machinery, the clearance between blade tips and the casing must account for thermal and inertial expansion as well as changes in concentricity due to shock loading events. To prevent catastrophic tip to casing contact, conservatively large clearances must be employed [11].

The role of abradable coatings is not only to allow for closer clearances, but to automatically adjust clearances, in-situ, to accept physical events and/or thermal scenarios that may be found in a devices operational history.

Abradable coatings improve safety and reduce fuel consumption and emissions in turbomachinery. Abradable materials are designed for critical turbomachinery clearance control applications (Figure – 1.12).

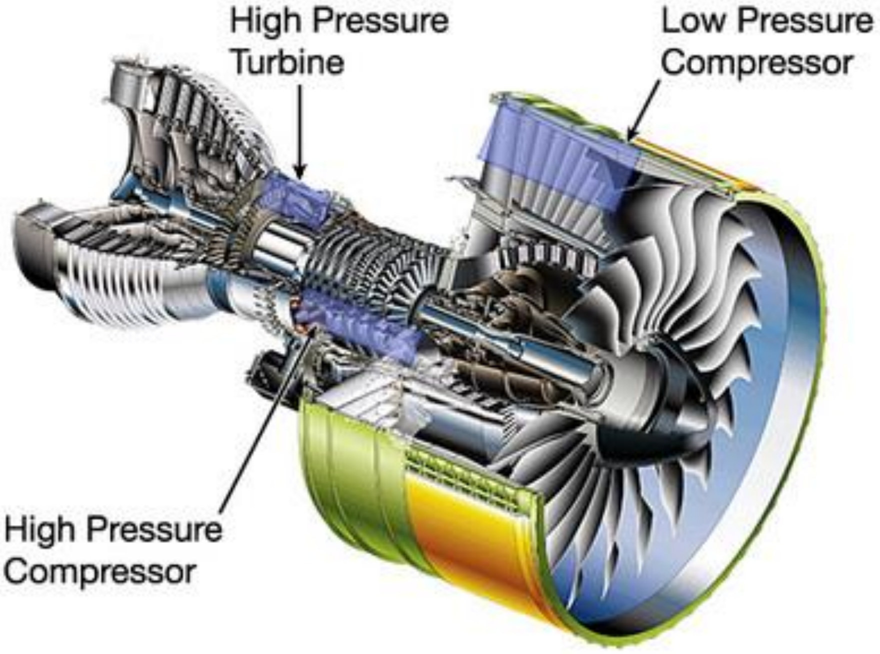


Figure – 1.12 Typical clearance control applications for aircraft turbine engines

Aircraft gas turbine engines applications

Typical applications:

- Rotor path linings.
- Low-, intermediate-, and high-pressure compressor seals.
- High-pressure turbine seals.
- Bearing air seals.
- Oil seals.

- Other labyrinth seal configurations.

Operational benefits:

- Reduces Specific Fuel Consumption (SFC).
- Increases compressor stall margins.
- Lowers engine Exhaust Gas Temperatures (EGT), extending the engine on-wing time.

Thermal barrier coatings

Thermal barrier coatings (TBC) are highly advanced materials systems usually applied to metallic surfaces, such as on gas turbine or aero-engine parts, operating at elevated temperatures, as a form of exhaust heat management. These coatings serve to insulate components from large and prolonged heat loads by utilizing thermally insulating materials which can sustain an appreciable temperature difference between the load-bearing alloys and the coating surface. In doing so, these coatings can allow for higher operating temperatures while limiting the thermal exposure of structural components, extending part life by reducing oxidation and thermal fatigue. In conjunction with active film cooling, TBCs permit working fluid temperatures higher than the melting point of the metal airfoil in some turbine applications.

Thermal barrier coatings typically consist of four layers: the metal substrate, metallic bond coat, thermally grown oxide, and ceramic topcoat. The ceramic topcoat is typically composed of ultra-stabilized zirconia (USZ) which is desirable for having very low conductivity while remaining stable at nominal operating temperatures typically seen in applications. Recent advancements in finding an alternative for USZ ceramic topcoat identified many novel ceramics (rare earth zirconates) having superior performance at temperatures above 1200 °C, however with inferior fracture toughness compared to that of USZ. This ceramic layer creates the largest thermal gradient of the TBC and keeps the lower layers at a lower temperature than the surface [12].

Thermal barrier coatings fail through various degradation modes that include mechanical rumpling of bond coat during thermal cyclic exposure, especially, coatings in aircraft engines; accelerated oxidation, hot corrosion, molten deposit degradation.

There are issues with oxidation (areas of the TBC getting stripped off) of the TBC also, which reduces the life of the metal drastically, which leads to thermal fatigue.

The TBC can also be locally modified at the interface between the bondcoat and the thermally grown oxide so that it acts as a thermographic phosphor, which allows for remote temperature measurement.

Interest in increasing the efficiency of gas turbine engines for aviation applications has prompted research into higher combustion temperatures. Turbine efficiency is strongly correlated with combustion temperature through the completeness of the combustion reaction. Lower temperature combustion breaks fewer hydrocarbon bonds and ultimately produces less thrust requiring more fuel. Thermal barrier coatings are commonly used to protect nickel-based superalloys from both melting and thermal cycling in aviation turbines. Combined with cool air flow, TBCs increase the allowable gas temperature above that of the superalloy melting point [13].

To avoid the difficulties associated with the melting point of superalloys, many researchers are investigating ceramic-matrix composites (CMCs) as high-temperature alternatives. Generally, these are made from fiber-reinforced SiC. Rotating parts are especially good candidates for the material change due to the enormous fatigue that they endure. Not only do CMCs have better thermal properties, but they are also lighter meaning that less fuel would be needed to produce the same thrust for the lighter aircraft.[3] The material change is, however, not without consequences. At high temperatures, these CMCs are reactive with water and form gaseous silicon hydroxide compounds that corrode the CMC.

$$SiOH_2 + H_2O = SiO(OH)_2$$

$$SiOH_2 + 2H_2O = Si(OH)_4$$

$$2SiOH_2 + 3H_2O = Si_2O(OH)_6$$

The thermodynamic data for these reactions has been experimentally determined over many years to determine that $Si(OH)_4$ is generally the dominant vapor species. Even more advanced environmental barrier coatings are required to protect these CMCs from water vapor as well as other environmental degradants. For instance, as the gas temperatures increase towards 1400 K-1500 K, sand particles begin to melt and react with coatings. The melted sand is generally a mixture of calcium oxide, magnesium oxide, aluminum oxide, and silicon oxide (commonly referred to as CMAS). Many research groups are investigating the harmful effects of CMAS on turbine coatings and how to prevent damage. CMAS is a large barrier to increasing the combustion temperature of gas turbine engines and will need to be solved before turbines see a large increase in efficiency from temperature increase.

In industry, thermal barrier coatings are produced in a number of ways:

- Electron Beam Physical Vapor Deposition: EBPVD
- Air Plasma Spray: APS
- High Velocity Oxygen Fuel: HVOF
- Electrostatic Spray Assisted Vapour Deposition: ESAVD
- Direct Vapor Deposition

Additionally, the development of advanced coatings and processing methods is a field of active research. One such example is the Solution precursor plasma spray process which has been used to create TBCs with some of the lowest reported thermal conductivities while not sacrificing thermal cyclic durability [14].

Wear resistant materials

Some of the materials for wear resistant coatings include ceramics such as carbides and metal oxides. Carbide coatings are produced in the form of cermets (ceramic and metal) they provide hardness and wear resistance coatings similar to solid sintered carbide components like carbide metal cutting tools. Metal oxides such as chromium oxide are also very hard and are very resistant to chemical attack so they can be an ideal solution when wear and corrosion are both present. Several metals and even some plastics are also used to provide wear resistant coatings (Figure 1.13-14).

- Carbide coatings are produced in the form of cermets (ceramic and metal). Cermets provide hardness and wear resistance coatings similar to solid sintered carbide components like carbide metal working tools.

- Tungsten carbide is an especially effective wear resistant coating, as it offers exceptionally high hardness levels (maximum 74 HRC hardness). Tungsten carbide is highly resistant to extreme temperatures below 650°C (1200°F) and corrosion.

- Metal oxides such as chromium oxide are also very hard and are very resistant to chemical attack so they can be an ideal solution when wear and corrosion are both present.
- Several metals and even some plastics are also used to provide wear resistant coatings [15].

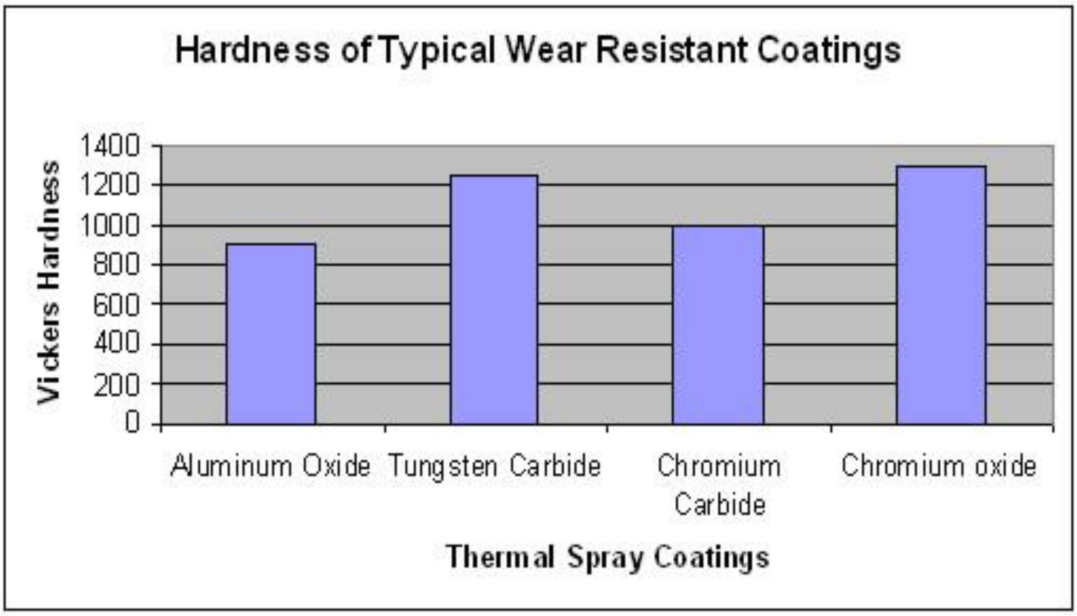


Figure 1.13 – Hardness of typical wear resistant coatings

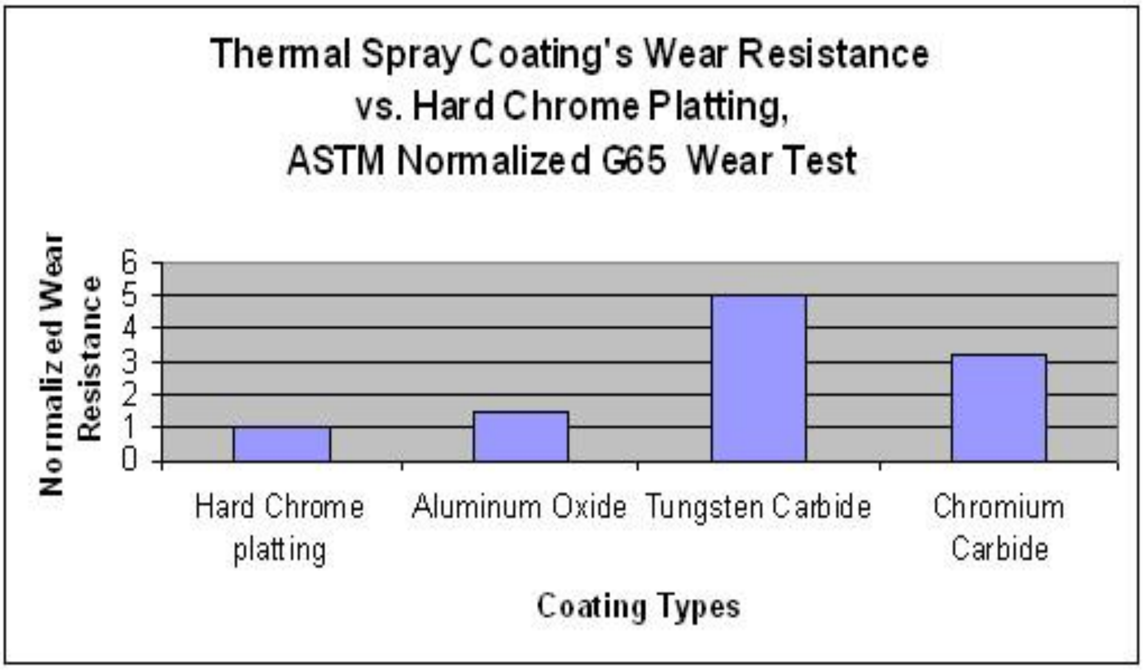


Figure 1.14 – Thermal spray coatings wear resistance (normalized)

Conclusions to part 1

Wear of metals occurs by the plastic displacement of surface and near-surface material and by the detachment of particles that form wear debris. This process may occur by contact with other metals, nonmetallic solids, flowing liquids, or solid particles or liquid droplets entrained in flowing gasses. It is important to prevent and timely repair wear damage

There are numerous ways to repair wear damaged surfaces. Further their development is extremely important in terms of increasing of production and repair efficiency of aeronautical equipment.

Fretting is one of the most dangerous factors that is impossible to be calculated by designers in the design of equipment. It appears in places where his not supposed to appear. Therefore it is necessary to devote more and more time for questions such as the damage to the elements of aircraft parts due to fretting.

PART 2 RESEARCH METHODOLOGY FOR WEAR RESISTANCE OF DETAILS FROM TITANIUM ALLOYS

2.1 Installation for investigation of wear of details from titanium alloys

Performing research in wear of details from titanium alloys characterized by a large variety of methods, in particular regarding the type and circuit loading of contact surface damage assessment. Selecting a method will be carried out in accordance with two requirements:

1. modeling wear of details from titanium alloys in the laboratory must be as close as possible to the conditions of occurrence of this type of surface damage to real structures;
2. selected method should enable a comparison of the results with those of other studies.

To test equipment due to the specificity of the wear of details from titanium alloys are following requirements:

1. fastening devices grip samples must be free from backlash;
2. the need to provide torsion rigidity and low distortion of the equipment;
3. choice of vibroslide movement with adjustable frequency and amplitude;
4. the presence of a controlled normal force to create the necessary contact pressure.

Domestic and foreign scholars have used these types of contact as a sphere - plane, cylinder – plane, cylinder - sphere, cylinder - cylinder and a plane - plane. Research is conducted usually in a laboratory, with samples in constant contact for a particular load. Different types of contact have their advantages and disadvantages. The disadvantages of the contact plane - plane include unequal conditions of deterioration of working sections of the samples, since the amplitude of movements under such a scheme is directly proportional to the distance from the axis of rotation. This disadvantage is eliminated by choice of the optimal geometry of one of the samples. In other types of contact occurs uneven pressure distribution in the contact area, which leads to the different conditions of wear [16].

The basis of the adopted methodology for conducting a comprehensive study of the work put quality parameters of friction tribocouple. The scheme of plane -plane contact type used at the facility МФК-1 (ГОСТ 23.211-80), the general form of which is shown in Fig. 2.1.

The main advantages of this method are:

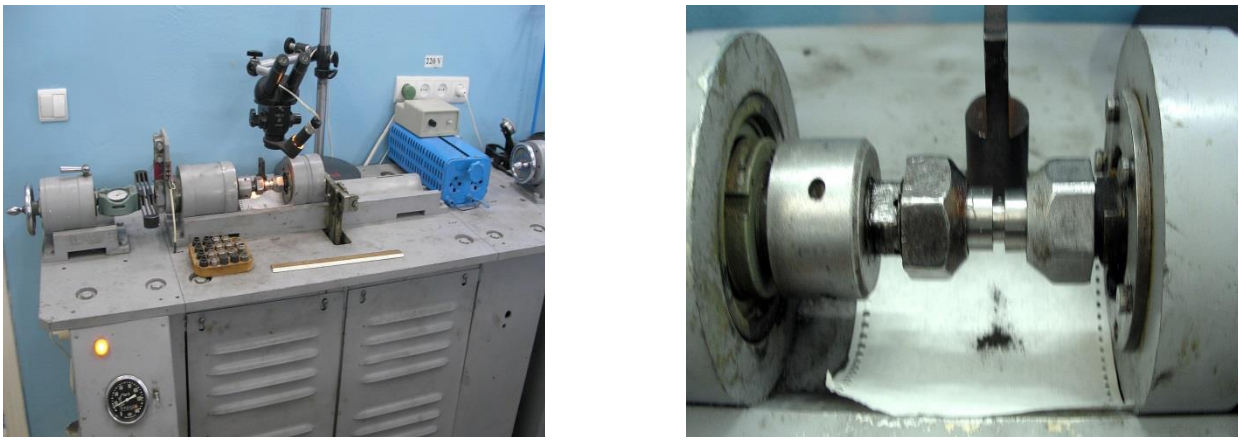
- The ability to quickly assess durability of materials and coatings in a fretting;
- Preparation of satisfactory results with a minimal amount of research test samples;
- The simplicity of the method and related equipment;
- Possibility of stepless regulation for frequency, amplitude of the normal load and micromovings;
- Testing using a plastic or liquid lubricants;
- Registration of friction force during the test.

The choice of a flat circular contact and swing movement of the contact surfaces due to the need to control the normal load and eliminate the edge effect.

The essence of the method lies in the fact that the movable cylindrical sample (counter samle) contact to real end of the cylindrical sample at a given pressure performs swing movement with a predetermined amplitude and frequency. The number of cycles - given after the test is measured by the real depreciation of the sample and concludes that the wear resistance of the material [17].

A schematic diagram of the installation of МФК-1 is shown in Figure 2.1-2.2. The installation operates as follows. The motor 17 transmits rotary motion of the eccentric 16 with adjustable eccentricity. Speed and number of revolutions are registered by device 1. The eccentric 16 via the connecting rod 15 is connected to the side scene 13 of drive shaft 12 performs swing movement of counter sample 11. The amplitude of the movement of counter sample 11 is regulated by eccentric adjusting device 16 and 14. The fixed pattern 10 is fixed in the self-centering chuck 9, which is mounted on the shaft 8 mobile headstock 7. Loading of the samples is carried out by loading device 5. The size of the axial load on the samples is recorded by dynamometer 6 (ЗИП 02-79 type ДОСМ-3-0,2; ГОСТ 2283-79) with a limit of measurement from

0.2 to 2 kN. Registration of friction force is carried out by the device 4 (НО 71.5М) through the amplifier 3 (8-Анч-7М) using tenzobeam 2. The number of cycles is controlled by meters which is installed on the front panel of the unit.



a) b)

a) - general view of the installation; b) – Collet position of МФК-1 with samples

Figure 2.1 – Exterior installation МФК-1 for fretting research

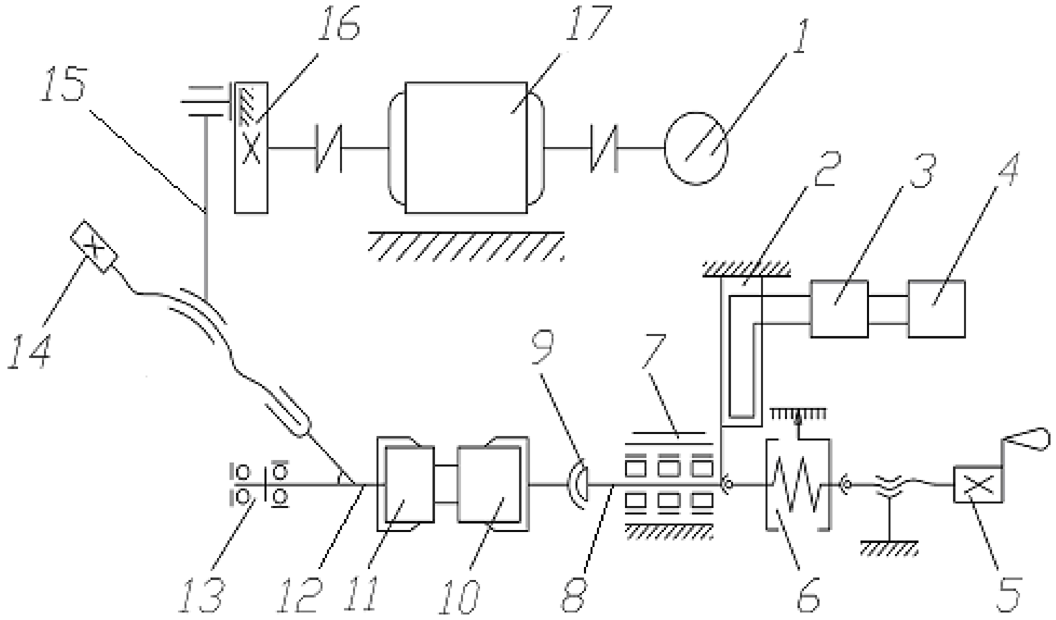
The amplitude of oscillation is controlled by changing the eccentric (roughly), and varying the length of the shoulder horizontal rod (exactly). Coarse adjustment allows adjusting its amplitude value in the range from 10 to 1000 microns, more precisely - from 5 to 15 microns. The amplitude of the relative movement is determined as the difference amplitude of vibrations of movable and immovable samples. Amplitude measurement is performed directly on the samples using an optical microscope binocular МБС-2, x8 - 98 using the stroboscopic effect [18].

Installation allows to make experiment with the following parameters:

1. Loading samples with axial forces from 200 to 1000 N;

2. Swing movement of sample immovable relative to the counter sample frequency of 10 to 30 Hz and an amplitude of 10 to 1000 microns;

3. The measuring system of installation allows during the experiment a continuous recording of the number of cycles of reciprocating motion of counter samples with an error of not more than 50 cycles.



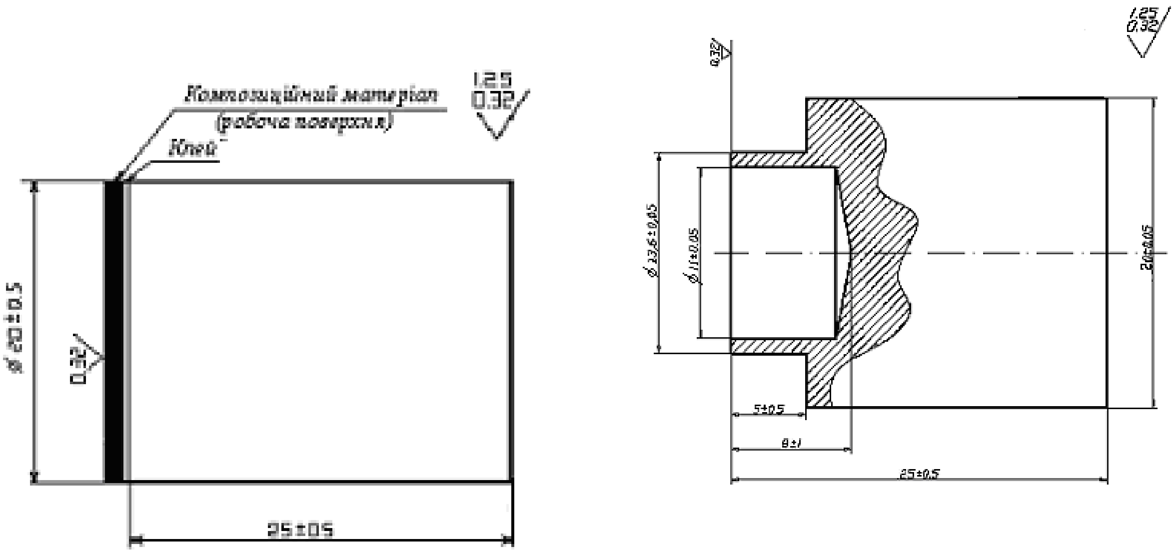
1 – rev counter, 2 – tenzobeam 3 – amplifier, 4 – recording equipment, 5 – load device 6 – dynamometer 7 – mobile chuck, 8 – shaft movable carrier 9 – self-aligning collet, 10 – a fixed sample 11 – mobile sample (counter sample), 12 – drive shaft swing mechanism 13 – 14 rocker - adjusting device 15 – a vertical rod, 16 – eccentric, 17 – the electric motor

Figure 2.2 – Schematic diagram of the installation МФК-1

2.2 Test samples for wear testing of details made from titanium alloys

Drawings of samples for research are presented in Figure 2.3. Contact of the test specimens is performed on the surface, on a closed ring with a nominal contact area 0,5sm^2, inner diameter 11mm and an outer diameter of 13.6 mm.

The samples were washed and dried before and after the experiment. The liquids used for washing are gasoline ГОСТ 443-76, ГОСТ 2603-79 acetone, ethyl alcohol ГОСТ 18300-72. Before carrying out tests and the labeling of measuring and recording equipment are checked.



а) б)

a) - a fixed pattern; b) - mobile sample (counter sample)

Figure 2.3 – Samples for research of wear

2.3 Measurement of wear

Measurement of deterioration of samples is carried out using a vertical type optimeter ИКВ profilograms by removal of the eight sections of the working surface of the sample in a radial direction Fig. 2.3. An important advantage of the method of determining the wear line is that the wear amount is not dependent upon the specific weight of the material and possible changes in sample weights [19].

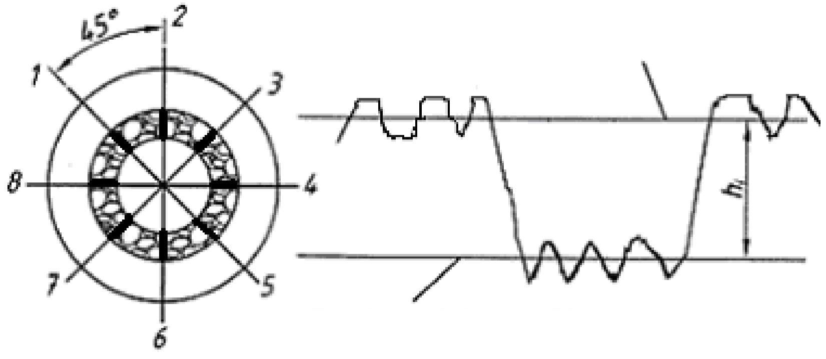


Figure 2.4 – Scheme of wear measuring samples after research of wear

Wear h_m of the sample is determined by the formula (2.1):

$$h_m = \frac{\sum_{i=1}^{8} h_i}{8} \qquad (2.1)$$

where h_i - profilograph distance on the track friction between the center lines of the initial profile and working surfaces.

However, carrying out the measurement by optimeter, the middle line of the original surface profile is almost impossible to determine directly (as a needle positioned exactly on the center line of the original surface profile and thus expose the zero line in the eyepiece optimeter very difficult). Therefore, we must use the method proposed below (see. Figure 2.4. Thus, seven points are measured at eight sites as follows: one on the right and left as close as possible to the working surface and five points on the surface of the working portion. Thus, the previous value is wear is measure (we call it the notional value of depreciation) [20].

The value of this quantity reckon from mark 0 - 0 of optimeter line (which can be seen through the eyepiece) to the triangle (to the left), which can be located on the top (positive value) or below (negative value) - see Figure 2.5, on the right.

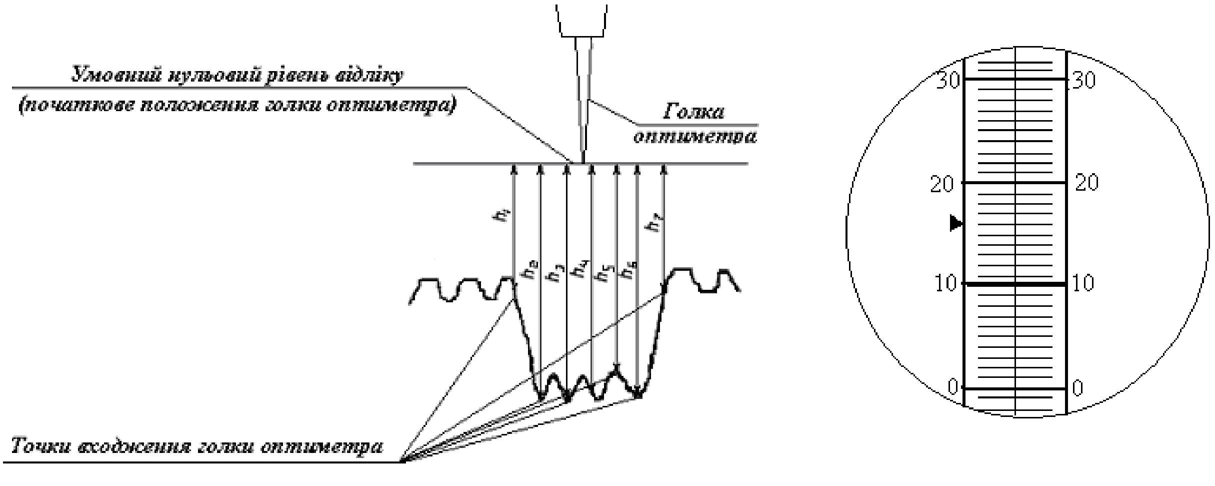


Figure 2.5 – Droving of the previous measurement (conventional) with the help of wear optimeter (left) and an example of pre-determining the amount of wear equal to 16 microns (right).

First, find the average value of the previous amount of wear on the edges close to the working surface (figure 2.4.):

$$h_{ср_{край}} = \frac{h_1 + h_7}{2} \tag{2.2}$$

The difference between h_1 and h_7 should not exceed 10 mkm.

Then we find the average value of the notional amount of wear on the work surface:

$$h_{ср_{РП}} = \frac{h_2 + h_3 + h_4 + h_5 + h_6}{5} \tag{2.3}$$

Finally, we find the difference between (2.3) and (2.2), which is the real value of the wear on one of the eight sections of the working surface of the sample:

$$h_{зносу_v} = h_{ср_{РП}} - h_{ср_{край}} \tag{2.4}$$

Then the wear of the sample will be calculated by the formula

$$h_m = \frac{\sum_{v=1}^{8} h_{зносу_v}}{8} \tag{2.5}$$

Conclusions

1. Installation МФК-1 is intended to simulate the wear conditions. It has a number of advantages and allows us to carry out the necessary experiments on laboratory equipment.

2. Installation allows to carry out experiments on samples of any materials pasted on top of the working surface of the material 1 mm thick.

3. Method for determining wear of composite materials was based on the method of linear magnitude. This method is most suitable for these types of tests, because we reject the weighting factor.

PART 3 EXPERIMENTAL DATA PROCESSING

3.1 Results of fretting corrosion testing for plasma sprayed coatings

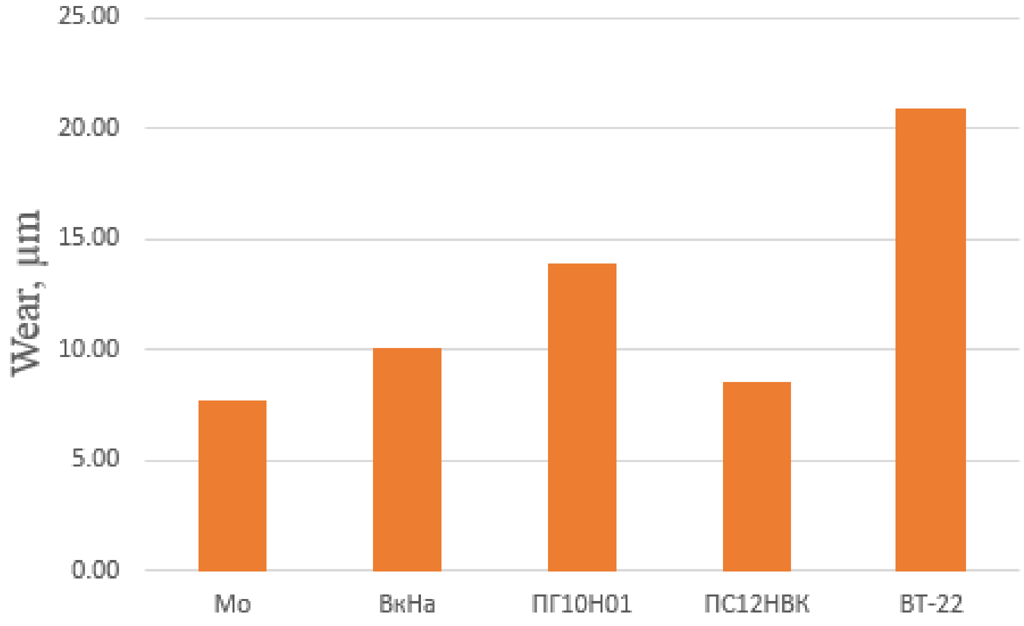


Figure 3.1 – Wear with amplitude 175 μm and load 20MPa

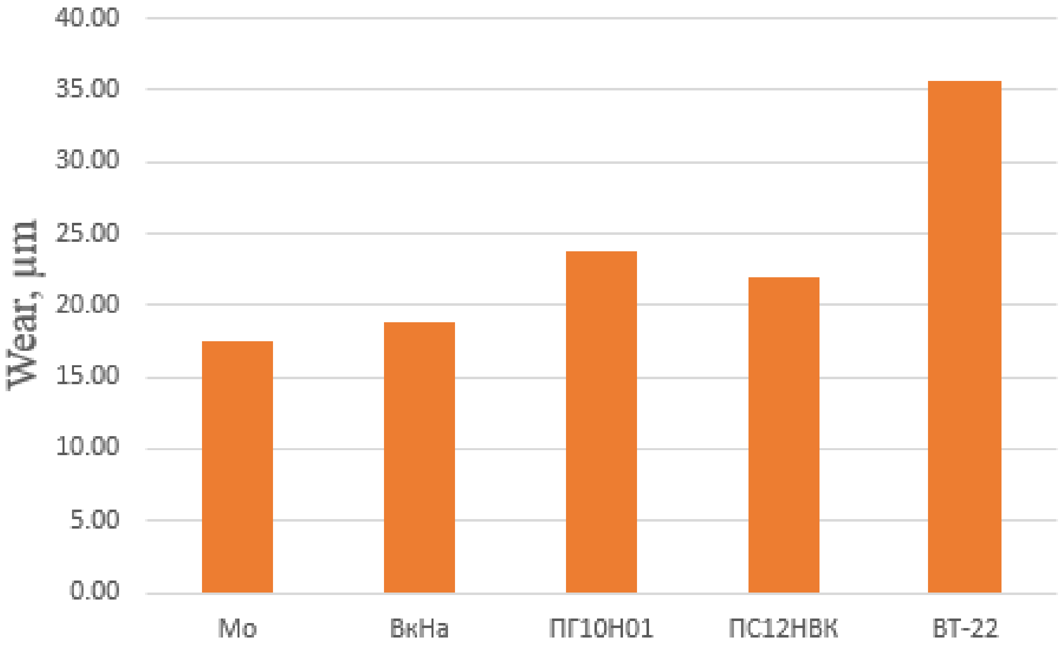


Figure 3.2 – Wear with amplitude 175 μm and load 30MPa

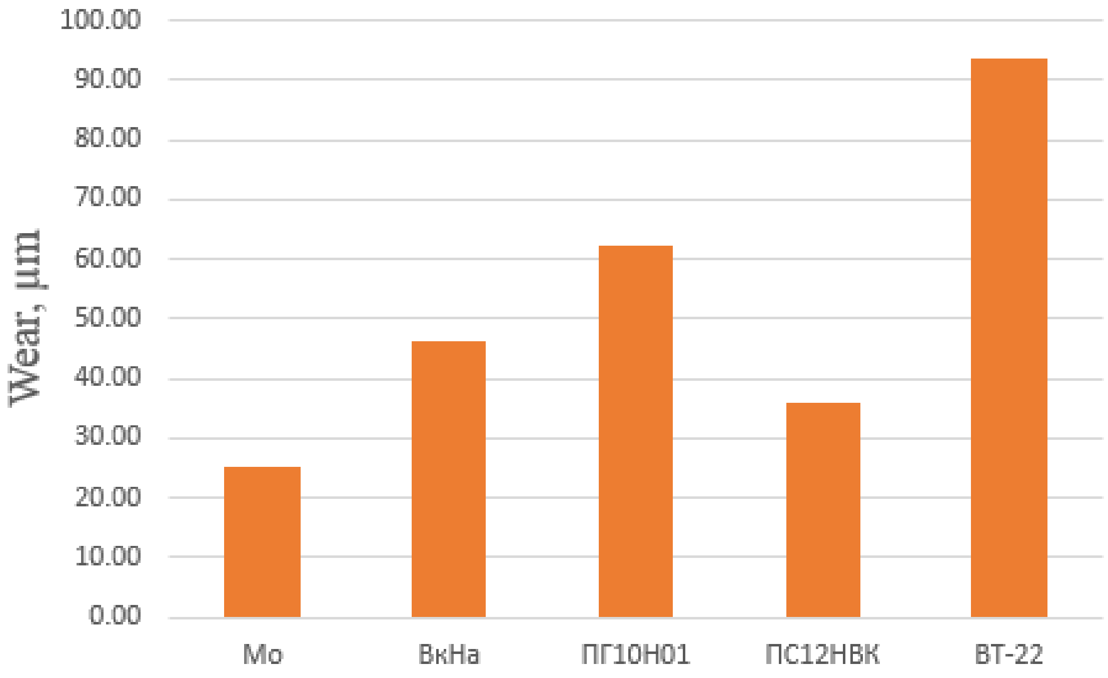


Figure 3.3 – Wear with amplitude 250 µm and load 20MPa

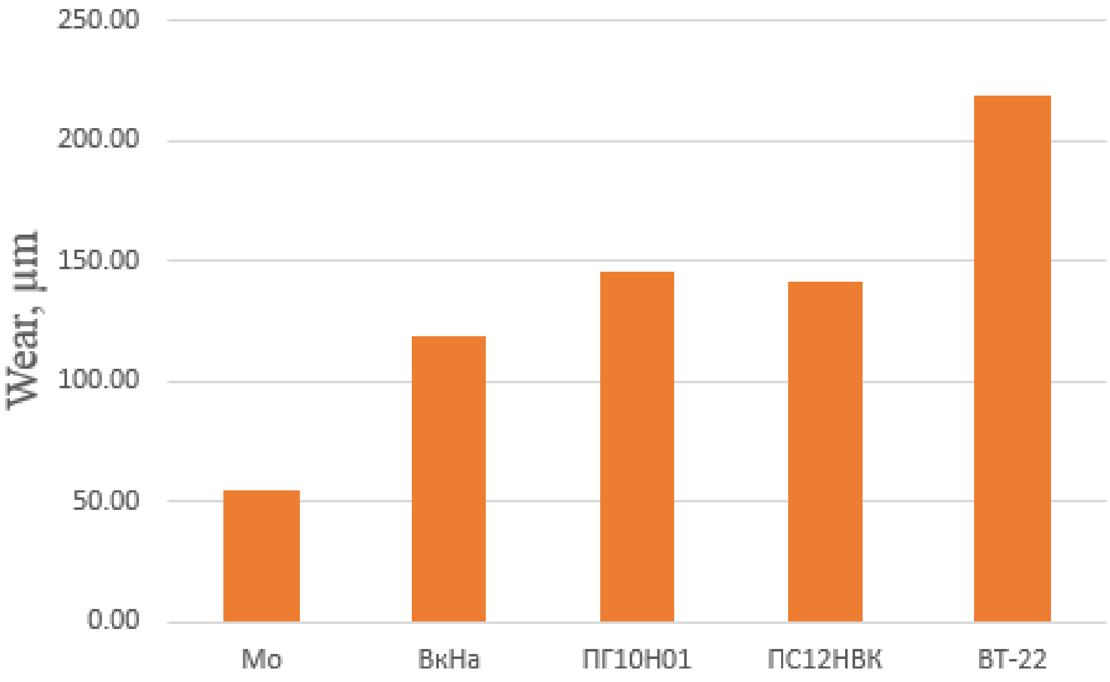


Figure 3.4 – Wear with amplitude 250 µm and load 30MPa

Bar chat shows that the most stable and least sensitive to change of amplitude of mutual displacement is molybdenum powder coating. Such coating has almost linear character which is similar to others researched plasma coatings at whole range of amplitudes of 200-250 µm and increases slowly after 250 µm. It should be noted that

Mo coatings shown the best wear resistance parameters at fretting at whole range of amplitudes from 50 to 300 μm and load range from 10 to 40 MPa.

Short description of used coatings [21-23]:

Molybdenum has a very good adherence strength due to its extreme metallurgic properties. The molybdenum wire has a melting point at ca. 2600 °C and creates oxide at ca. 700 °C. Therefore molybdenum should only be used up to an operational temperature of 300 °C.

Molybdenum coatings have a hardness of 60-66 HRc depending on the coating method used and are perfect for the manufacture of wear-resistant coatings. Molybdenum is also ideally suited for bearing seats for waste salvation in maintenance. Molybdenum has better sealing properties than a hardened agent.

Molybdenum cannot be used on copper, >20 % Cu alloys, chromed or nitrated parts. However, Molybdenum can and is used on hardened base agents to obtain improved sealing properties.

A molybdenum coating by wire flame spraying can be a high quality base coat. Subsequently Cr steel, bronze or ceramic can be applied.

The advantage of molybdenum coating (ca. 60 -100 °C) also in comparison with welding is that the thermal exposure of the work piece can be disregarded and deformations can be excluded in large surfaces too. The disadvantage is that hollow spaces or difficult accessible places (recipients, undercuts, inner pipes etc.) cannot be treated with molybdenum coating.

The group of **ВкНа** powders includes nickel powder aluminum, NiTi, iron chrome aluminum alloys obtained by reduction of oxides, the production of which is carried out since 1980 and which has accumulated extensive experience in technology, properties of materials and their use in various fields of engineering thermal coatings. The group also includes a wear resistant NiTi alloy powder RP-Ni55Ti45, obtained in the same manner as other metalides of group A, but without the inherent nikel aluminium alloys heat resistant.

A characteristic feature of this type of powder is irregular, rather, dendritic particle shape. Powders of this class is obtained by reduction of metal oxides with calcium hydride. The resulting Ni-Al, Ni-Ti, Fe-Cr-Al are polydisperse powders and contain 90-95 % of the particles ranging in size from 11 to 63 microns.

Due to the developed surface of the powder particles in the plasma spraying a sufficiently compact and durable coating.

Powder **ПГ-10Н-01** is composed of nickel-base Ni-Cr-B-Si-C-Fe. The hardness is regulated by contents of C, B, Cr. Spraying compounds have a low coefficient of friction, high allowable operating temperature (800 °C); they are used for spraying and spraying melting at restoring parts of carbon, stainless steels, cast iron: the type of "shaft", piston pumps, valves, chamfers, crankshaft journals, pushers. When the hardness of up to HRC 40 cover cutting process, more than 40 HRC - grinding.

Powder **ПС-12НВК-01** (HRC 57-64) consists of the composition: powder ПГ-10Н-01 (65 %) of the tungsten carbide powder + WC (35 %). The coatings of this composition have high wear resistance. They are used to restore the movable and fixed joints. Coating treated by grinding.

3.2 Analysis of acquired data

Defining of charachteristical types of traces of friction after fretting tests allows to find characteristics of surface destruction and define main mechanism of surface wear.

At figure 3.5 traces of friction of plasma coatings and pure titanium alloy ВТ-22 after testing for fretting is shown.

During fretting friction of sprayed coatings there are always oxides appearing at their surface. Their change in colors shows change of processes at friction zone.

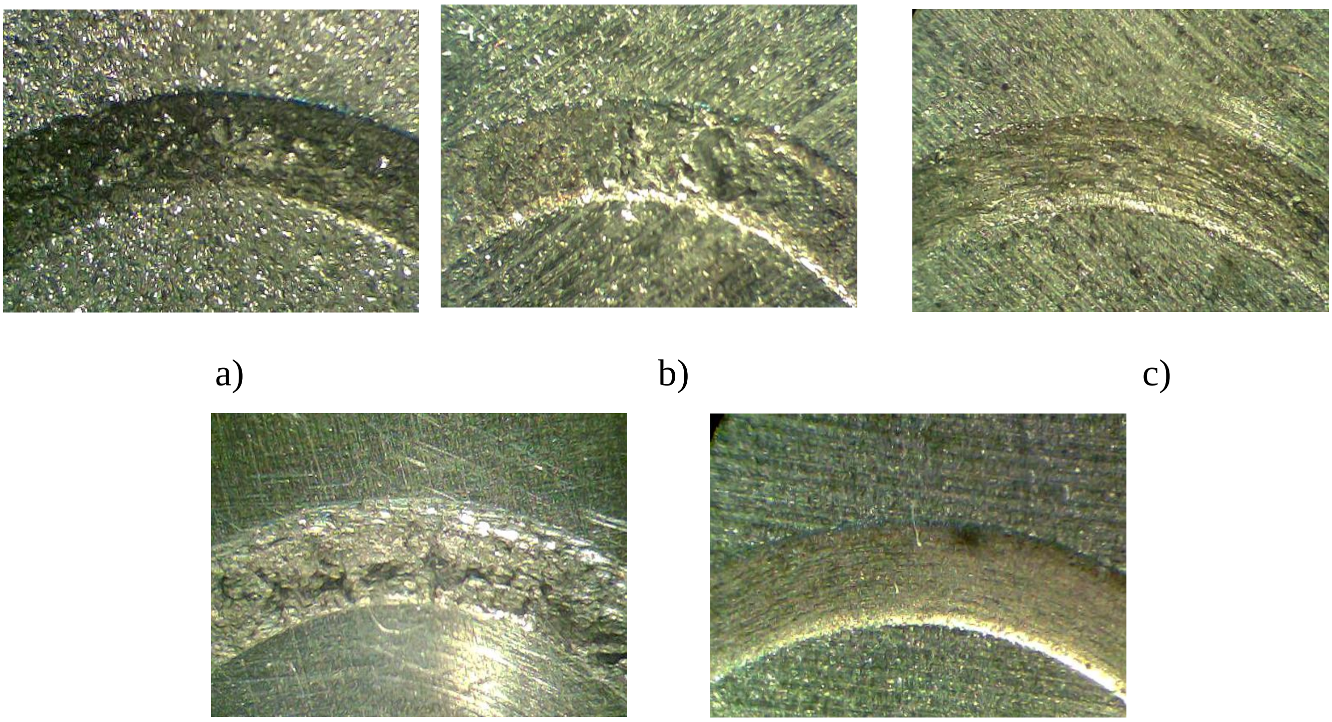
During friction at ВКНА coating oxides were changing in color from dark brown to light brown-red colors.

Oxides at ПГ10Н-01 were changing in color from black to light brown colors.

Oxides at ПС12НВК-01 were changing in color from black to light brown and light grey colors.

Molybdenum oxides colors were changing from black to dark blue-grey color. Molybdenum actively smeared at rear sample, moreover molybdenum oxides is a finely dispersed powder that works as grease during friction.

During friction of rear sample at titanium alloy BT-22 there were smearing of alloy at rear sample due to tendency to cold welding and further friction on itself.



a) b) c)

d) e)

a) – Mo, b) – ПС12НВК-01, c) – ВКНА, d) – ПГ10Н-01, e) – ВТ-22.

Figure 3.5 – Friction traces of plasma coatings during fretting tests.
(A-175 μm, P-20MPa)

Conclusions to part 3

1. With amplitude change there is a change in wearing rate. There is some defined point at which type of wear changes from mechanically-chemical to fatigue-abrasive that changes the type of wear from linear to abrasive. Numerical value depends on condition of loading and is equal: for 10-30 MPa - 200-230 μm, for 40 MPa - 170-180 μm.

2. Plasma coating of molybdenum shown most stable results at wide range of loads and amplitudes.

PART4 LABOR PROTECTION

Improvement of work conditions is made by means of conservation of health and workability of worker, economy of alive work in the way of increasing of level of usage of working time, economy of social work in the way of increasing of production quality, improvement of usage of main industrial founds, decreasing of number of emergency situations.

We consider the work of the technicianon the basis ofspraying of metal onto part or mechanism being repaired.Technicianworking conditionsrequirestrict implementationand compliance withthe rules oflabor precaution.This part of diploma project includes as working out of general questions of labor precaution so special questions of labor precaution, which are connected with the theme that is projected in the diploma – *Aviation components repair by means of thermal spraying*.

4.1 Analysis of dangerous and harmful factors for subjects of labor precaution

The subject of analysis is a technician.

The object is a thermal spraying booth.

Accordingly to Міждержавний стандарт ГОСТ 12.0.003-74 (1999) ССБТ «Опасные ивредные производственные факторы. Классификация». when performing thermal spraying on existing staff affects the following dangerous and harmful production factors, under:

- **Increased noise level**

Metal spraying equipment uses compressed gases, which create noise. Sound levels vary with the type of spraying equipment, the material being sprayed, and the operating parameters. Typical sound pressure levels are measured at 1 meter behind the arc.

- **High brightness of light**

Combustion spraying equipment produces an intense flame, which may have a peak temperature more than 3,100 °C, and is very bright. Electric arc spraying produces ultra-violet light, which may damage delicate body tissues. Spray booths, and enclosures, should be fitted with ultra-violet absorbent dark glass. Where this is not possible, operators, and others in the vicinity should wear protective goggles containing BS grade 6 green glass. Opaque screens should be placed around spraying areas. The nozzle of an arc pistol should never be viewed directly, unless it is certain that no power is available to the equipment.

- **Increased dust and fumes in workplace air**

The atomization of molten materials produces a large amount of dust and fumes made up of very fine particles (about 80 – 95% of the particles by number <100 nm). Proper extraction facilities are vital, not only for personal safety, but to minimize entrapment of re-frozen particles in the sprayed coatings. The use of respirators, fitted with suitable filters, is strongly recommended, where equipment cannot be isolated. Certain materials offer specific known hazards:

1. Finely divided metal particles are potentially pyrophoric and harmful when accumulated in the body.
2. Certain materials e.g. aluminum, zinc and other base metals may react with water to evolve hydrogen. This is potentially explosive and special precautions are necessary in fume extraction equipment.
3. Fumes of certain materials, notably zinc and copper alloys, have a disagreeable odor and may cause a fever-type reaction in certain individuals (known as metal fume fever). This may occur some time after spraying and usually subsides rapidly. If it does not, medical advice must be sought.
4. Fumes of reactive compounds can dissociate and create harmful gasses. Respirators should be worn in these areas and gas meters should be used to monitor the air before respirators are removed [24].

- **Increased temperature of the working area**

Combustion spraying guns use oxygen and fuel gases. The fuel gases are potentially explosive. In particular, acetylene may only be used under approved conditions. Oxygen, while not explosive, will sustain combustion, and many materials will spontaneously ignite, if excessive oxygen levels are present. Care must be taken to avoid leakage, and to isolate oxygen and fuel gas supplies, when not in use.

- **High voltage in an electrical circuit, which closure may occur through the human body**

Electric arc guns operate at low voltages (below 45 V dc), but at relatively high currents. They may be safely hand-held. The power supply units are connected to 440 V AC sources, and must be treated with caution.

4.2 Analysis of working conditions and development of protective measures

Accordingly to Міждержавний стандарт ГОСТ 12.1.005-88 ССБТ. «Общие санитарно-гигиенические требования к воздуху рабочей зоны». Міждержавний стандарт ГОСТ 12.1.007-76 ССБТ. «Вредные вещества. Классификация и общие требования безопасности».

Owners and operators of thermal metal spraying equipment should contact their equipment manufacturer and spray material suppliers to ensure that the equipment is being used according to recommended operating parameters. These parameters may include work piece pre-heat, distance from metal spraying gun to work piece, and power supply settings.

Due to the numerous hazards associated with this process, it is not possible to describe all the control measures that apply to thermal metal spraying in this document. See the Sources of information section at the end of this document for additional resources [25].

In summary, the following control measures are recommended for thermal metal spraying.

Metal fumes, dusts, and gases:

Where feasible, provide local exhaustventilation to remove contaminants from the air. The system must be carefully designed to ensure that it will adequately capture contaminants and must be cleaned and serviced periodically to ensure optimal ventilation efficiency. Electrostatic precipitation or wet collection of overspray may be used to scrub the exhausted air stream. Emissions limits imposed by environmental agencies may influence the choice of technology used to capture and contain contaminants. HEPA filters may be required if working with relatively toxic materials.

Conduct air sampling to characterize workers’ exposure to airborne contaminants. Thermal metal spraying can generate metal fumes, dusts, gases, and vapors at concentrations that exceed their respective Permissible Exposure Limits (PELs).

Establish a respiratory protection program.This means medical screening of workers, proper selection and fitting of respirators, and worker training. Correct respirator storage and cleaning and an evaluation of the program are needed.

Positive-pressure, air-supplied respirators are recommended when spraying toxic metals and should be provided to the operator and any helpers.

Ensure that workers are not exposed to exhaust gases from the thermal metal sprayer’s power generator. Power generators should be located and operated outside the building in a well ventilated area. This is essential to minimize the risk from carbon monoxide and also to avoid the creation of nickel carbonyl.

Increased noise level reduction.

Accordingly to ДСН 3.3.6.037-99 «Санітарні норми виробничого шуму, ультразвуку та інфразвуку»:

Establish a hearing conservation program that includes audiometric testing, noise monitoring, hearing protection devices, training, and recordkeeping.

4.3 Fire Safety Rules at the workspace

Requirements of fire and explosion prevention

Accordingly to НАПБ А.01.001-2004 Правила пожежної безпеки в Україні:

The basic precautions for thermal spraying are essentially the same as for welding and cutting.

Airborne, finely divided solids or accumulations of such, especially metal dusts, should be treated as explosives. To minimize danger from dust explosions, adequate ventilation should be provided to spray booths. A wet collector of the water wash type is recommended to collect the spray dust. Bag or filter-type collectors can be used only after consultation with those experienced and knowledgeable in the field [26].

Sludge from wet collectors should be disposed of using methods that apply to this type of waste.

Good housekeeping in the work area should be maintained to avoid accumulation of metal dusts, with particular attention given to inspecting for dust on rafters, tops of booths, and in floor cracks. The extremely hot condition of thermal spraying operations requires additional precautions such as, not pointing thermal spraying equipment that is in operation at any person or at material that will burn.

Certain hydrocarbon decreasing solvents and sealer bases are flammable, toxic and carcinogenic, and special handling precautions need to be exercised relative to their use, handling and storage, in and about the thermal spray area. Paper, wood, oily rags, or cleaning solvents can cause fire and should not be stored or contained within the spray areas.

Storage and Handling of Compressed Gas Cylinders

Local, state, municipal, and Federal regulations relative to the storage of cylinders should be investigated and complied with.

Oil or grease on oxygen equipment can be extremely dangerous due to explosive hazard. Only special oxidation-resistant lubricants may be used with oxygen equipment. When in doubt, consult a qualified dealer or the equipment manufacturer.

Manifolding of cylinders is frequently required in thermal spraying work. Use only the appropriate regulator for each gas cylinder.

If a flow meter with glass tubes is used, a protective shield should be placed between the flow meter and the gun. Also, back flow preventive devices should be used together with flow meters to avoid unsafe operating conditions and to ensure proper flame balance.

Hose and hose connections should be installed. Avoid damage to hoses. Use hoses only for the purpose for which they were designed.

Compressed air should be referred to by its proper name to avoid confusing it with oxygen or fuel gas. Air, oxygen or fuel gas should not be used to clean clothing. Use compressed air for thermal spraying or blasting operations only at pressures recommended by the equipment manufacturers [27].

4.4 Instructions on labor precaution

Instruction for labor precaution during gas-thermal spraying is developed in accordance with НПАОП 0.00-4.15-98 «Положення про розробку інструкцій з охорони праці». Наказ Держнаглядохоронпраці від 29.01.1998 р. № 9.

1. General requirements for labor protection

1.1. To perform gas-thermal coating and electric arc method (hereinafter - spraying), are allowed men over 18 years that have passed a medical examination, appropriate training and instruction, verification of knowledge of labor protection requirements and having the skills to service the equipment.

1.2. Admission to the metalizer issued an order for the organization after induction and the issuance of the certificate of verification of knowledge of labor protection.

1.3. A review and examination of labor protection and industrial hygiene should be performed at least once in a quarter marked in a special and personal card of metalizer.

At least once a year a check knowledge by a special commission under the chairmanship of the worker assigned to the employer. The results of examination shall be made a metalizers protocol with number which appears on the certificate and the seal of the organization.

1.4. Employees must undergo periodic medical examinations in the prescribed manner.

1.5. The employee is obliged to comply with the established in the organization of work and rest.

1.6. In the process of spraying an employee may impact these dangerous and harmful production factors:

- Increased dust and gas content of the working area;
- High frequency noise;
- Elevated levels of ultrasound;
- High brightness light;
- Increased surface temperature of products and equipment;

- Neuropsychiatric overload.

1.7. In preparing the surface of the base metal before spraying is necessary to ensure the following precautions:

- Mechanization and automation of the process;
- Sealing processes, which are a source of harmful and hazardous production factors;
- The use of ventilation and local exhausts;
- The use of locking systems;
- The use of screens, covers and other protections;
- Ensure acoustic protection;
- Use of dust collecting systems.

1.8. The blast cells should be provided with a lock.

1.9. The use of dry silica sand to clean parts is not allowed.

1.10. When cleaning the surface of the base metal for spraying there must be leak-proof rooms and remote management.

1.11. Start of cleaning chambers (drums) should be blocked with the start of ventilation.

1.12. Compressed air before entering the cleaning chamber must pass through a moisture separator.

1.13. Operations for filling and cleaning powders in silos installations for spraying should be carried out with the use of local suction or in special chambers and cabins equipped with exhaust ventilation.

1.14. During the deposition process should be applied manually portable local pumps, providing the concentration of harmful substances in the air at regulated level.

1.15. Gas-thermal coating method is necessary to comply with the following requirements:

- Injection in the sputtering gas flow passages of the burner must be not less than 0,012 MPa;
- All units and details related to communication of flammable gases shall be sealed;

- For main voltage areas of consumption of oxygen and flammable gases should be set gas reversion prevention posts, equipped with gates, preventing the spread of kickback to the gas pipeline;
- If powered by single cylinder between the balloon and the metalizer reducers should be installed safety device.

1.16. The design of the torch for thermal coating with the ignition of the combustible mixture should provide ignition without kickback.

1.17. When coating the electric arc method must meet the following requirements:

- Open circuit voltage DC power supply with manual process should not exceed 80 V, with automatic or mechanical process - 90 V;
- Spray heads electric vehicles should ensure stable combustion of an electric arc;
- Electrometalizer must be equipped with a device to protect workers from the effects of an electric arc;
- Cross section lead wires to electrometalizer should provide long-term operation without heating above 50 °C;
- Mounting sleeve to the air pipe and fitting the device must be reliable and to exclude the possibility of failure.

1.18. For manual coating there must be soundproof cabins or special sections with soundproof enclosures.

1.19. The presence of outsiders in the area of placement of equipment cleaning and coating during operation or adjustment is restricted, it must be ensured by the presence of safety signs, made in accordance with ГОСТ 12.4.026.

1.20. When carrying out spraying metalizers must be provided with personal protective equipment (PPE).

1.21. Protective equipment that is issued on an individual basis, need to be in the workplace metalizer during work.

1.22. When working on the coating affecting the noise should not exceed the values established by ГОСТ 12.2.003. If you exceed the maximum permissible noise levels employees must use hearing protectors.

1.23. When working on the coating in closed vessels, and spray materials that emit toxic fumes and dust (lead, zinc, tin, copper, cadmium), you must use the full face mask with forced air for breathing.

1.24. To protect your eyes from the flame and molten metal particles, the operator must wear safety goggles with RFP filters.

1.25. Clothes should be comfortable and does not restrict movement of metalizer, to protect it from sparks, splashes and industrial pollution of molten metal.

1.26. All clothing of metalizers must be periodically washed.

1.27. To protect their hands metalizers should be provided with gloves.

1.28. Usage of the protective clothing and gloves made from synthetic materials is prohibited.

1.29. Metalizer in addition to these instructions should know:

- Emergency response plans at the workplace;
- Manual-gun;
- Instruction on fire safety in the workplace;
- Rules for the use of PPE;
- CPR and first aid in case of accidents;
- Good personal hygiene.

1.30. Staff should be able to provide first aid in case of poisoning, burns of the skin and mucous membranes, an electric shock.

When working on the coating must be the means for first aid in a special place: a sterile bandage, tourniquet, adhesive tape, bandages, tincture of iodine, ammonia, syringe for washing, ointment for burns.

1.31. Employees are responsible for the violation of this instruction, in accordance with applicable law.

2. Requirements of labor protection before starting work

2.1. Inspect, tidy up and put on clothing and footwear.

2.2. Check the accuracy and completeness of the PPE.

2.3. Inspect the workplace to remove from it anything that can interfere with work, to free passes and not to overload them.

2.4. Prepare a soapy solution to check the tightness of equipments connections.

2.5. Check the equipment for spraying (metalizer) hoses, power supplies.

2.6. Check the accuracy of hoses, tools, fixtures, gauges, gear, and the presence of choke in the equipment.

2.7. Check the tightness of all split and soldered joints.

2.8. Clean oil and moisture from the air or gas that transport sprayed material.

2.9. Check the operation of ventilation.

2.10. Check for a faulty light.

2.11. Inspect the primary means of fire suppression.

3. The requirements of occupational safety during operation

3.1. Work on the spraying done only in overalls and with the use of PPE.

3.2. Prior to joining the reducer to the cylinder valve should be checked for:

- The presence of seals or other markings (paint) on the safety valve, indicating that the factory or after repair adjustment is not broken;
- Serviceability of the gauge and the term of the audit;
- The state of the thread fittings;
- The seal on the valve;
- The presence of the input filters fittings.

3.3. Securing the hoses at the connection nipples-gun must be reliable - special clamps must be used.

3.4. For gas-gun:

- Carry out a preliminary adjustment of the feed rate of powder or wire;
- Light the gas flame on duty, and then select the desired rate of supply of powder or wire;
- Conduct spraying uniformly moving metalizer; distance the spray nozzle from the surface of the base metal should be 150 - 180 mm.

3.5. For electrometalizers:

- Open the air valve;
- Lay the wire on the spool so that it unwinds during operation; the wire should be clean, smooth and free of oxides and films;
- Recharge the device with wire;
- Without power set settings and adjustments of the spray head;
- Turn on the wire: wire end has to be in the center of the air nozzle at a distance of 2 - 3 cm from the outer end of the nozzle;
- Conduct spraying: For best results, work at a maximum pressure of compressed air (0.5 - 0.6 MPa).

3.6. When applying coatings need to avoid heating the surface of the plate over 70 ° C.

3.7. Use the-gun for thermal spraying prohibited at:

- Injection into the gas flow passages less than 0.12 MPa;
- Tightness assemblies and parts-gun;
- With crude oil and moisture from the air or other gas transporting the spray material.

3.8. Do not use an arc-gun:

- Without a protective screen on the air cap;
- When malfunction;
- Without PPE.

3.9. It is forbidden to make setup and adjustment of the spray head electric-powered device.

3:10. Repair of gun and other equipment in the workplace is prohibited.

4. Requirements of labor protection in emergencies

4.1. In the event of dangerous situations that can lead to accidents or incidents metalizer obliged to inform the emergency department or the chief safety engineer.

4.2. If you have any flashback immediately close the valves of the gas-gun and cool spray head.

4.3. In case of internal or external heat source (ignition), which can lead to an explosion of cylinders, you should immediately evacuate the cylinders. If unable to remove them from the danger zone to be cooled with water balloons until they are completely cool.

4.4. In the event of a fire:

- Stop the wire;
- Disconnect the equipment used;
- Call the fire department, the head of operations and start fire extinguishing.

4.5. In case of accident victim or witness shall notify the shop superintendent (shift) or craftsmen who have to organize first aid to the victim.

4.6. If injured, stop work, notify the supervisor and seek medical help.

5. Requirements of labor protection at the end of work

5.1. After termination of the gas-gun is necessary:

- Close the valves of the cylinders;
- To release gases from all communications;
- Free compression springs gears;
- Disconnect hoses;
- Clear metalizer from accumulated dust and wipe thoroughly;
- Blow metalizer with compressed air.

5.2. After termination of the electrometalizer you should:

- Switch off the wire;
- Turn off the current;
- Close the air valve;
- Clear metalizer from accumulated dust and wipe thoroughly;
- Blow driving and pressure rollers of the wire feeder with compressed air;
- After 30 hours from the beginning of the work replace the grease in the gear.

5.3. Remove and clean clothing, PPE.

5.4. Wash your face and hands with warm water and soap, take a shower.

5.5. Turn off the lights.

5.6. Report to the master completion of work and leave the workplace only with the permission of the master.

Conclusions to part 4

Safety at work - a multifaceted concept, under it should be understood not only ensure the safety of workers during the performance of their duties, in fact, it covers a variety of activities. For example, prevention of occupational diseases, organization of proper rest and nutrition workers during work breaks, providing them with essential clothing and hygiene facilities and even implementation of social benefits and guarantees. The correct approach to safety at the plant, competent use of different methods of intangible incentives give employees a sense the last necessary reliability, stability and leadership in the interest of the employees. Thus, thanks to well-functioning labor safety and reduced turnover, which in turn positively affects the stability of the whole enterprise.

Studying and solving problems related to ensuring healthy and safe environment in which to labor rights - one of the most important tasks in developing new technologies and production systems. Research and identify possible causes of industrial accidents, occupational diseases, accidents, explosions, fires, and development activities and requirements aimed at addressing these causes can create a safe and favorable conditions for labor rights. Comfortable and safe working conditions - one of the main factors that affect the performance and safety of health workers.

PART 5 ENVIRONMENTAL PROTECTION

5.1 Analysis of thermal spraying process influence on an environment

Air pollution and hazardous materials are increasingly becoming a consideration of business and the thermal spray industry is no exception. Laws such as the Clean Air Act (CAA) and the Resources Conservation and Recovery Act (RCRA) have recently been clarified and given enforcement “teeth" by Congress. National Ambient Air Quality Standards (NAAQS) and Hazardous Waste Disposal regulations are being implemented and enforced. Their implementation is changing the way in which manufacturing businesses are being operated and are permitted to operate.

The ASM International has issued in early 1994 an “Environmental Guideline” for the thermal spray industry, as the culmination of its past 30 months of work in collaboration with industry sponsors [28].

It has been found that the typical questions which are asked and continue to permeate the industry are: hazardous materials applied to thermal spraying, air pollutants applied to thermal spraying, limits for air emissions, thermal spray shop compliance with air emission regulations, measurement and calculation of plant’s air emissions, thermal spray health and pollutant risk, hexavalent [$\mathrm{Cr}_{(VI)}$ or $\mathrm{Ci}_{6}+$], hexavalent Cr generation in thermal spraying, control of emissions, acceptance by regulators, hazardous waste in thermal spray shops.

After a preliminary review was completed, it was clear that the largest challengefacing the thermal spray industry is EDUCATION education in the relevant laws and regulations as well in the processes and their potential to generate emissions and/or waste materials which fall under control by State and U.S. regulatory oversight. The project has been conducted over the two (2) years and has been a painstaking review of literature, regulations, reviews with agencies, and a collection task from “corporate” files of the sponsors or other responsible thermal spray industry members.

The thermal spray industry does not have a hazardous air or solid emissions problem. What it does have, however, is an education and understanding problem regarding what the industry produces as emissions, what are the relevant regulations and responsibilities, and what are the relevant control technologies and procedures. It can be stated that the perceived problem comes from implementation of regulations guided by federal laws, mostly stemming from the Clean Air Act (CAA) (revised from 1970 to 1990) and the Resource Conservation and Recovery Act (RCRA) of 1976 and amended in 1984. California, Texas. New York. Connecticut, and Pennsylvania, as well as many other states now draw many of their regulations from these laws, which hold the states ultimately responsible for regulation. Many states set specific limits on pollutants and hazardous materials defined by federal guidelines.

5.2 Operational actions for thermal spray emissions decreasing

The laws and state agencies are regulating the emissions from spray booths, the installation or modification of equipment in the handling of many coating and cleaning materials, and in the disposal of waste materials. There is educated and reported significant information and concluded that the thermal industry, as a whole or even individual shops/facilities, are not significant pollution sources, however, they have the responsibility to meet all laws and regulations. For example, the thermal spray industry handles and potentially emits pollutants and hazardous materials. Pollutants include particulate materials less than 10 nm (PM10), ozone, NO_x, CO, hydrocarbons; while hazardous materials include such materials as chromium, nickel, copper, cobalt, aluminum, and zinc. It was found, generally, that the thermal spray industry uses and emits pollutants and hazardous materials, when using filtration, at such low levels that except in high pollution areas, such as the Los Angeles Basin (an F.PA Non-attainment Area) that permitting of facilities should be no problem. Generally, the problems encountered to date have come from the user and/or the regulatory agency not having sufficient knowledge, understanding or information [29].

Air pollution/emissions from thermal spray processes which utilize inert, combustible, and oxidizing gases and heat metals, ceramics, and polymers (initially powder or rod/wire form) are either in a particulate or gaseous forms. These processes produce exhaust gas jets of combusted and/or heated gases, generally ranging from 50 to 1500 slm in which solid or molten particulate travel and in which some fumes and/or vapors (particle sizes are typically less than 1 nm) are generated. These process pollutant exhausts and the hazardous materials, particularly containing chromium and/or nickel compounds, arc what concern any environmental regulation and are what bring this industry under agency scrutiny. There is reported that the typical types of air and solid waste emissions from thermal spray coating processes and demonstrated that when controlled, emissions are well within all regulations.

The most potent hazardous material which the thermal spray industry generally uses is chromium, which, when in its hexavalent (Cr_6+) state, becomes a potent cancirogen. However, when in its neutral state (metallic) or other ionic states, (except the trivalent (Cr_3+)). the effect of chromium is benign. Thermal spray uses many chromium-containing alloys or compounds (NiCr. stainless steels, chromium carbides, and chromium oxides) which arc heated, sometimes to their vapor states, where it is believed that some small fraction of the chromium oxides in the presence of moisture or the atmospheric contaminants form some chromates. It is in this form that some concentrations of the trivalent and the hexavalent states occur [30-32].

The major reason for such EPA scrutiny is the use in the industry of materials considered as hazardous, in particular, chromium appears to be singled out. Chromium compounds, with the possible conversion to Cr_3+ or Cr_6+. are severely restricted to the lowest concentration levels of any common material outside the plant, these levels (GCL's) range from 00002 to 1 nm/m^3, depending on the acceptable risk assigned. Concentrations are at ground level at the perimeter of plant where the general public is exposed and are determined by the quantity of the emissions, the concentrations emitted at the stack and the dispersion conditions relate to prevailing atmospheric conditions, models for calculating the areas prevailing dispersion conditions are available through local environmental agencies.

Many corrosion-resistant and high-temperature wear coatings contain chromium or chromium compounds, hence its use by the thermal spray industry. Based on measurements taken in the industry in the past few years, Cr_6+ emissions levels, without controls, can typically be about 1 lb/per day for a large shop (one with more than $10 million / year in spraying revenues). However, with controls such as dry cartridge filtration systems with HR PA filters, whose reported efficiencies exceed 99.99 %, these emissions can be kept well below 0.00001 lbs/day. Typical atmospheric dispersion will then reduce this to below acceptable levels. PM10 (particulate below 10 pm size), nickel, copper, cobalt, aluminum, and zinc are also to be controlled but have GLC limits 10 to 10,000 times that of Cr_6+, which means that, given the efficiencies of today’s air emission controls. 10 to 10,000 lbs of these materials could be sprayed without exceeding the emissions levels. Gaseous emissions are not controlled by filtration, but with concentration limits of NOx (GCL<100 pgm/m^3). ozone (GCL<235 pgm/m^3). related to plasma and wire arc spray operations, and CO (GLC<30,000 pg/m) or hydrocarbons (volatile organic compounds known as V.O.C.'s) related to combustion spraying are expected to be below these limits in normal operation with ventilation. Despite the assumption, however, industry measurements of these gaseous emissions still need to be documented.

A review of the available air emissions control technologies indicates that dry filtration, incorporating cartridge type systems, in combination with high-efficiency particle absorption (HEPA) filters meet the Maximum Achievable Control Technology (MACT) standard. It has been concluded, based on the limited and documented data that do exist, that with the incorporation of such filtration. air emissions in the thermal spray industry can be controlled to meet all air district air quality standards, including the strictest found in the South Coast Air Quality District of California (which includes the Los Angeles basin). Best Available Control Technology (BACT) may, however, be allowed with smaller sources or in certain attainment areas, permitting the use of less expensive air filtration equipment such as bag houses, wet scrubber filters, or other technology. Each thermal spray shop must work with its local environmental control agency. The major problem in the industry which still persists is the permitting and the reporting procedures in the various “air districts" around the country. Each new permit raises questions, both by the shops and the regulatory agencies, regarding what is required, what has been measured, what arc the emissions, and what are acceptable controls.

Usage of these methods allows to reduce emissions more than by 99.99 % (Table 5.1 –5.9)

Table 5.1 – Thermal Spraying Emission Factors for Hexavalent Chromium.

	Emission Factors (lbs Cr+6/lb Cr sprayed)*			
Operation	0% Control Efficiency (Uncontrolled)	90% Control Efficiency (e.g. Water Curtain)	99% Control Efficiency (e.g. Dry Filter)	99.97% Control Efficiency (e.g., HEPA Filter)
Single-Wire Flame Spray	4.68E-03	4.68E-04	4.68E-05	1.40E-06
Twin-Wire Electric Arc Spray	6.96E-03	6.96E-04	6.96E-05	2.09E-06
Flame Spray	6.20E-03	1.17E-03	6.20E-05	1.86E-06
HVOF	6.20E-03	1.17E-03	6.20E-05	1.86E-06
Plasma Spray	1.18E-02	6.73E-03	2.61 E-03	2.86E-06
Other Thermal Spraying	7.17E-03	2.05E-03	5.70E-04	2.01E-06

*Some emission factors are based directly on stack test results while others are calculated values, derived from stack test results and control efficiencies.

Table 5.2 – Thermal Spraying Emission Factors for Nickel

Operation	Emission Factors (lbs Ni/lb Ni sprayed)*			
	0% Control Efficiency (Uncontrolled)	90% Control Efficiency (e.g. Water Curtain)	99% Control Efficiency (e.g. Dry Filter)	99.97% Control Efficiency (e.g., HEPA Filter)
Twin-Wire Electric Arc Spray	6.0E-03	6.0E-04	6.0E-05	1.8E-06
Flame Spray	1.10E-01	4.64E-02	1.10E-03	3.30E-05
HVOF	1.10E-01	4.64E-02	1.10E-03	3.30E-05
Plasma Spray	1.5E-01	3.67E-02	1.5E-03	1.72E-05
Other Thermal Spraying	9.4E-02	3.25E-02	9.4E-04	2.13E-05

*Some emission factors are based directly on stack test results while others are calculated values, derived from stack test results and control efficiencies

5.3 Emissions parameters calculation

Thermal Spraying Inc. operates two thermal spraying booths. One booth is used for plasma spraying and the other booth is used for flame spraying and twin-wire electric arc spraying. Listed below is information on the facility’s operations [33-38].

Table 5.3 – Thermal Spraying Inc. operation information

Booth	Control Device	Operation	Materials Used	Quantity Used	% Total Chromium	% Nickel
Booth #1	HEPA Filter	Plasma Spray	Powder ABC	25 lbs/yr	25%	0%
			Powder XYZ	50 lbs/yr	20%	75%
Booth #2	Dry Filter (99% effic.)	Flame Spray	Powder 123	10 lbs/yr	0%	95%
			Powder XYZ	75 lbs/yr	20%	75%
		Twin-Wire	Wire #1	80 lbs/yr	20%	5%

An example calculation is provided below for Thermal Spraying Inc.:

Step 1: Identify all thermal spraying materials that contain at least 0.1 % by weight of chromium (Cr), chromium compounds, nickel (Ni), or nickel compounds.

The following four products contain chromium or nickel: Powder 123; Powder ABC; Powder XYZ; Wire #1.

Step 2: Determine the total percentage of chromium and/or nickel.

Table 5.4 – Percentage usage of chromium and/or nickel.

Materials Used	% Total Chromium	% Nickel
Powder 123	0%	95%
Powder ABC	25%	0%
Powder XYZ	20%	75%
Wire #1	20%	5%

If a thermal spraying material contains a compound, include only the portion that is chromium or nickel. For example, if the material contains 95 % chromium oxide (Cr_2O_3), the weight percent of chromium would be calculated

Step 3: Compile the annual material usage.

Table 5.5 – Annual material usage

Operation	Materials Used	Quantity Used
Plasma Spray	Powder ABC	25 lbs/yr
	Powder XYZ	50 lbs/yr
Flame Spray	Powder 123	10 lbs/yr
	Powder XYZ	75 lbs/yr
Twin-Wire	Wire #1	80 lbs/yr

Step 4: Calculate the annual usage quantities for chromium and nickel.

Table 5.6 – Annual usage quantities for chromium and nickel

Materials Used	Quantity Used	% Total Chromium	% Nickel	Qty. of Total Chromium Used	Qty. of Nickel Used
Powder ABC	25 lbs/yr	25%	0%	[25 lbs/yr]x[25% Cr] = 6.25 lbs Cr/yr	[25 lbs/yr]x[0% Ni] = 0 lbs Ni/yr
Powder XYZ	50 lbs/yr	20%	75%	[50 lbs/yr]x[20% Cr] = 10.0 lbs Cr/yr	[50 lbs/yr]x[75% Ni] = 37.5 lbs Ni/yr
Powder 123	10 lbs/yr	0%	95%	[10 lbs/yr]x[0% Cr] = 0 lbs Cr/yr	[10 lbs/yr]x[95% Ni] = 9.5 lbs Ni/yr
Powder XYZ	75 lbs/yr	20%	75%	[75 lbs/yr]x[20% Cr] = 15.0 lbs Cr/yr	[75 lbs/yr]x[75% Ni] = 56.25 lbs Ni/yr
Wire #1	80 lbs/yr	20%	5%	[80 lbs/yr]x[20% Cr] = 16.0 lbs Cr/yr	[80 lbs/yr]x[5% Ni] = 4.0 lbs Ni/yr

Based on this emission level, Thermal Spraying Inc. is below the Tier 1 threshold for hexavalent chromium. Therefore, no new control efficiency requirements would be imposed by this ATCM because of hexavalent chromium emissions. However, Thermal Spraying Inc. will still need to comply with the permitting, monitoring, and recordkeeping requirements of the ATCM. In addition, if the workload increased and emissions exceeded Tier 1 thresholds, it would be necessary to upgrade the dry filter system or limit the usage of all chromium materials to the booth that has the HEPA filter.

Step 5: Identify the applicable emission factors.

Table 5.7 – Applicable emission factors

Control Device	Operation	Emission Factor - Hexavalent Chromium (lb Cr+6/lb Cr sprayed)	Emission Factor - Nickel (lb Ni/lb Ni sprayed)
HEPA Filter	Plasma	2.86E-06	1.72E-05
Dry Filter (99% effic.)	Flame	6.20E-05	1.10E-03
	Twin-Wire	6.96E-05	6.0E-05

Step 6: Calculate annual emissions ([Annual Emissions] = [Emission Factor]*[Annual Usage].) For hexavalent chromium, the annual emissions are

Table 5.8 – Annual emissions for hexavalent chromium

Booth	Control Device	Operation	Materials Used	Qty. of Total Chromium Used (lbs Cr sprayed/yr)	Emission Factor (lb Cr+6/lb Cr sprayed)	Annual Emissions (lb Cr+6/yr)
#1	HEPA Filter	Plasma Spray	Powder ABC	6.25	2.86E-06	[6.25]x[2.86E-06] = 1.79E-05
			Powder XYZ	10.0	2.86E-06	[10.0]x[2.86E-06] = 2.86E-05
#2	Dry Filter (99% effic.)	Flame Spray	Powder 123	0	6.20E-05	[0]x[6.20E-05] = 0
			Powder XYZ	15.0	6.20E-05	[15.0]x[6.20E-05] = 9.30E-04
		Twin-Wire	Wire #1	16.0	6.96E-05	[16.0]x[6.96E-05] = 1.11E-03
					Total =	0.002

For nickel, the annual emissions are

Table 5.9 – Annual emissions for nickel

Booth	Control Device	Operation	Materials Used	Qty. of Nickel Used (lbs Ni sprayed/yr)	Emission Factor (lb Ni/lb Ni sprayed)	Annual Emissions (lb Ni/yr)
#1	HEPA Filter	Plasma Spray	Powder ABC	0	1.72E-05	[0]x[1.72E-05] = 0
			Powder XYZ	37.5	1.72E-05	[37.5]x[1.72E-05] = 6.45E-04
#2	Dry Filter (99%effic.)	Flame Spray	Powder 123	9.5	1.10E-03	[9.5]x[1.10E-03] = 1.05E-02
			Powder XYZ	56.25	1.10E-03	[56.25]x[1.10E-03] = 6.19E-02
		Twin-Wire	Wire #1	4.0	6.0E-05	[4.0]x[6.0E-05] = 2.40E-04
					Total =	0.073

Based on this emission level, Thermal Spraying Inc. is below the Tier 1 threshold for nickel. Therefore, no new control efficiency requirements would be imposed by this ATCM because of nickel emissions. However, Thermal Spraying Inc. will still need to comply with the permitting, monitoring, and recordkeeping requirements of the ATCM. In addition, if the workload increased and emissions exceeded Tier 1 thresholds, it would be necessary to upgrade the dry filter system or limit the usage of all nickel materials to the booth that has the HEPA filter.

Step 7: Calculate the maximum hourly emissions for nickel.

- Powder 123 is the material that has the highest weight percentage of nickel (95 %).
- The maximum spray rate for the flame spraying gun is 10 lbs/hr.
- The emission factor for flame spraying is 1.10E-03 lb Ni/lb Ni sprayed.

The maximum hourly emissions for nickel are 0.01 lbs Ni/hr, which is well below the compliance limit of 0.1 lb Ni/hr for point sources. Therefore, this thermal spraying operation complies with the maximum hourly limit for nickel.

Conclusions to part 5

Nowadays there is satisfactory situation with thermal spray emissions around the world, but there is importance to improve thermal spraying connected peoples' knowledge about possible emissions factors/materials/ways to reduce the emission.

Emissions of thermal spray shops are hardly restricted by authorities' regulatory organizations.

There are following ways to reduce thermal spraying emissions:

- dry filtration
- incorporating cartridge type systems
- high-efficiency particle absorption (HEPA) filters

Thus, gas-thermal coating methods are an integral part of the production of modern wear-resistant parts that do not substantially affect the environment.

GENERAL CONCLUSIONS

Wear of metals occurs by the plastic displacement of surface and near-surface material and by the detachment of particles that form wear debris. This process may occur by contact with other metals, nonmetallic solids, flowing liquids, or solid particles or liquid droplets entrained in flowing gasses. It is important to prevent and timely repair wear damage

There are numerous ways to repair wear damaged surfaces. Further their development is extremely important in terms of increasing of production and repair efficiency of aeronautical equipment.

Fretting is one of the most dangerous factors that is impossible to be calculated by designers in the design of equipment. It appears in places where it is not supposed to appear. Therefore, it is necessary to devote more and more time for questions such as the damage to the elements of aircraft parts due to fretting.

Installation МФК-1 is intended to simulate the wear conditions. It has a number of advantages and allows us to carry out the necessary experiments on laboratory equipment.

Method for determining wear of composite materials was based on the method of linear magnitude. This method is most suitable for these types of tests, because we reject the weighting factor.

Plasma coating of molybdenum shown most stable results at wide range of loads and amplitudes.

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