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# Wear: A Serious Problem in Industry

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## Abstract

Wear is the damaging, gradual removal or deformation of material at solid surfaces. Causes of wear can be mechanical or chemical. The study of wear and related processes is known as tribology. Abrasive wear alone has been estimated to cost 1–4% of the gross national product of industrialized nations. The current chapter focuses on types of wear phenomena observed in the industries (such as abrasive wear, adhesive wear, fretting wear, fatigue wear, erosive wear and corrosive wear), their mechanisms, application of surface coating for the protection of the surface from the industrial wear, types of surface coatings, thermal spray coating, types of thermal spray coating and its application in industry to protect the surface from wear. The detail information about the wear phenomena will help the industries to minimize their maintenance cost of the parts.

**Keywords:** wear, type of wear, tribology, surface coating, thermal spray coating

## 1. Introduction

Wear is the damaging, gradual removal or deformation of material at solid surfaces. Causes of wear can be mechanical also called as erosion or chemical also called as corrosion. Wear of metals occurs by plastic displacement of surface and near-surface material and by detachment of particles that form wear debris. In material science, wear is the erosion of material from a solid surface by the action of another solid. The study of the process of wear is the part of the theory of tribology. Wear in machine components, along with different cycles, for example, fatigue and creep, makes surfaces deteriorate, in the end prompting material degradation or loss of applicability. Subsequently, wear has enormous monetary significance as first mentioned in the Jost Report. Abrasive wear alone has been assessed to cost 1–4% of the gross national product of industrialized countries. Wear of metals happens by plastic dislodging of surface and close to surface material and by separation of particles that produce wear debris. The molecule size may change from millimeters to nanometers. This cycle may happen by contact with different metals, nonmetallic solids, streaming fluids, solid particles or fluid beads entrained in streaming gasses. The wear rate is influenced by components, for example, sort of stacking (e.g., stationary and active), kind of movement (e.g., gliding and continuing), surrounding temperature, and lubrication, specifically by the cycle of deposition and deterioration of the boundary lubrication layer. Contingent upon the tribosystem, diverse wear types and wear systems can be watched.

2. Industrial wear problems

The **Table 1** represents the various wear problems occur in the industries.

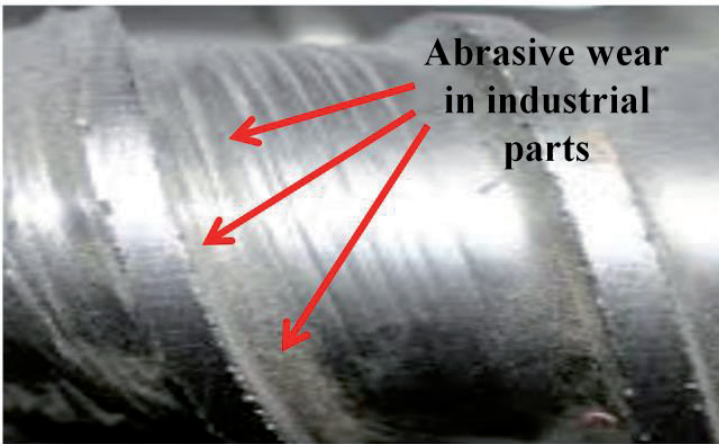
Sl no.	Industrial wear problems	Significant characteristic	Examples
1.	The wear of surfaces by hard particles in a stream of fluid	Erosion with one supply of erodent being continuously renewed in a gas or fluid	Valves controlling flow of crude oil laden with sand Gas pumping equipment
2.	The wear of surfaces by hard particles in a compliant bed of material	Abrasion, with supply of abrasive continuously renewed by movement of bed of material	Digger teeth. Rotors of powder mixes. Extrusion dies for bricks and tiles
3	Wear of metal surfaces in mutual rubbing contact, with abrasive particles present	Three body abrasion (solid abrasive-solid) with an ongoing supply of new abrasive particles	Pivot pins in construction machinery. Scraper blades in plaster mixing machines. Shaft seals for fluids containing abrasives
4.	The wear of metal components in rubbing contact with a sequence of other solid components	Adhesive wear and abrasion, but with one component in the wear process being continuously renewed	Tools used in manufacture, such as punching and pressing tools, sintering dies and cutter blades
5.	The wear of pairs of metal components in mutual and repeated rubbing contact	Adhesive wear, but with a wear rate that can be very variable depending on the detailed operating conditions	Piston rings and cylinder liners. Coupling teeth and splines. Fretting between machine components
6.	Component wear from rubbing contact between metals and non metals	Adhesive wear between two consistent components	Brakes and clutches. Dry rubbing bearings. Artificial hip joints

**Table 1.**  
*Examples of industrial wear problems.*

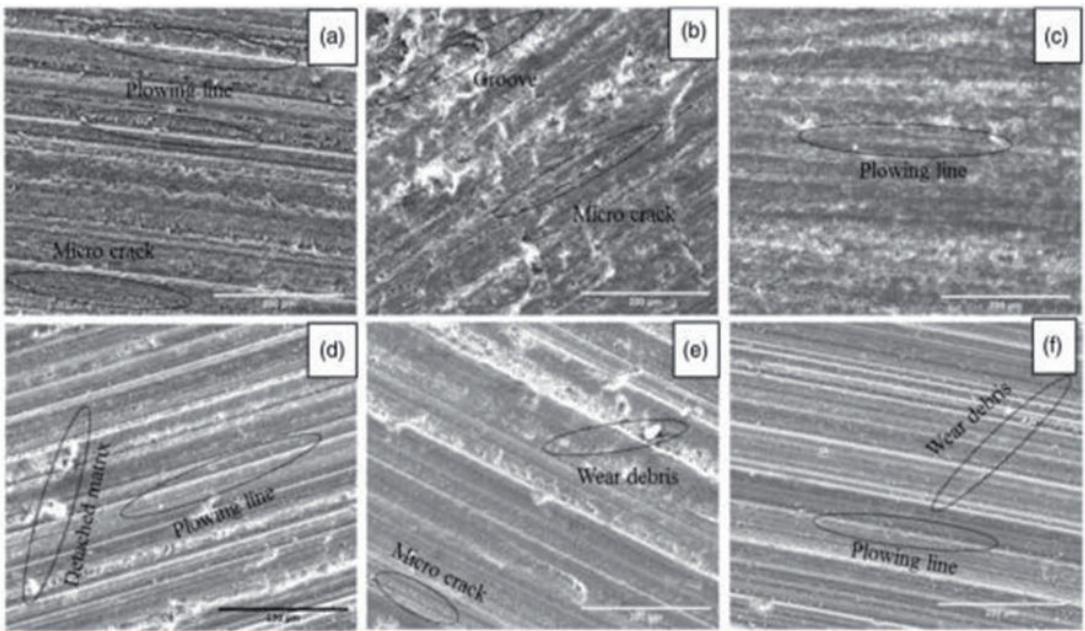
3. Types of wear

3.1 Abrasive Wear

Removal of material by the mechanical action of an abrasive is known as abrasive wear (**Figure 1**). Abrasives are substances which are usually harder than the abraded surface and have an angular profile. Examples: sand particles between contact surfaces, the damage of crankshaft journals in reciprocating compressors. Abrasive wear is ordinarily ordered by the kind of contact and the contact condition. The sort of contact decides the method of abrasive wear. The two methods of abrasive wear are known as two-body and three-body abrasive wear. Two-body wear happens when the sand or hard particles eliminate material from the contrary surface. The basic similarity is that of material being eliminated or dislodged by a cutting or plowing activity. Three-body wear happens when the particles are not constrained, and are allowed to roll and slide down a surface. The contact condition decides if the wear is delegated open or shut. An open contact condition happens when the surfaces are adequately uprooted to be free of each other. There are various components which influence abrasive wear and therefore the way of material removal. A small number of unique components have been proposed to illustrate the way where the outer material is eliminated.



**Figure 1.**  
*Abrasive wear of industrial parts.*



**Figure 2.**  
SEM image of worn surface after abrasive wear test of (a) neat epoxy, (b) 0.5 wt% CNF, (c) 1.0 wt% CNF, (d) 1.5 wt% CNF, (e) 2.0 wt% CNF and (f) 2.5 wt% CNF [1].

Khanam et al. [1] investigated about the abrasive wear resistance of CNF enforced epoxy nanocomposites at different percentage of CNF concentration. It has been observed (**Figure 2**) that the neat epoxy composite revealed deep plowing line, many microcracks and surface covered with wear debris of detached matrix over the entire worn surface.

### 3.2 Adhesive wear

When one surface slides over the other interaction between the high spots produces occasional particles of wear debris. Mild adhesion is the expulsion of films, for example, oxides at a lower rate. Severe adhesion is the evacuation of metal because of tearing, breaking, and liquefying of metallic intersections (**Figure 3**). This prompts scraping or annoying of the surfaces and even seizure.

Adhesive wear can be found between surfaces during frictional contact and by and large alludes to undesirable dislodging and connection of wear debris and material mixes starting with one surface then onto the next. Two glue wear types can be recognized.

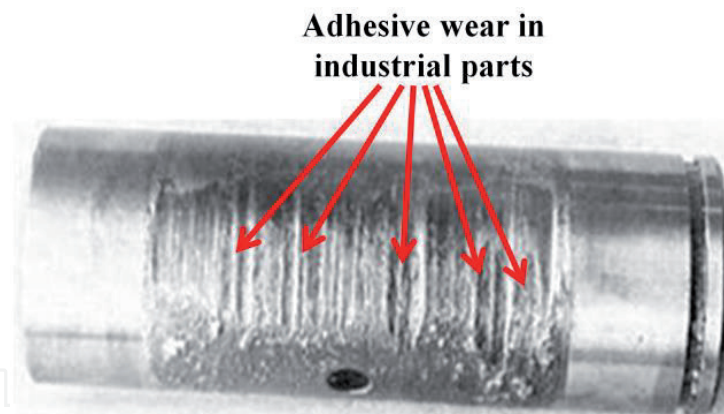


1. Adhesive wear is brought about by relative movement, “direct contact” and plastic deformation which make wear debris and material transfer starting with one surface then onto the next.
2. Cohesive adhesive load, holds two surfaces together despite the fact that they are isolated by a quantifiable separation, with or with no real exchange of material. By and large, glue wear happens when two bodies slide over or are squeezed into one another, which advance material exchange. This can be depicted as plastic distortion of little pieces inside the surface layers. The asperity or minute high focuses (surface roughness) found on each surface influence the seriousness of how sections of oxides are pulled off and added to the next surface, mostly because of solid adhesive force between atoms [2] yet in addition because of collection of vitality in the plastic zone between the severities during relative movement.

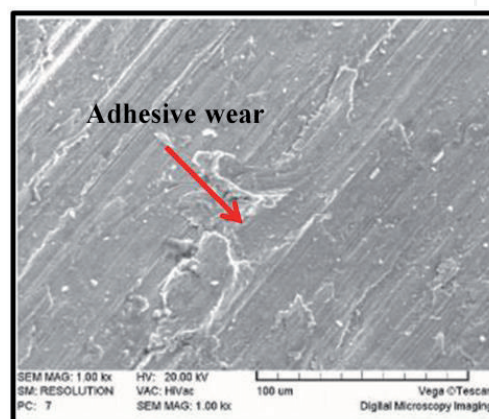
Yunxia et al. [3] investigated about the adhesive wear phenomena of aero-hydraulic spool valves and the investigation revealed the trimming and transformation of outer material due to the shear fracture of the bonded areas (**Figure 4**). It has been also claimed that the above mentioned work is an evidence of the adhesion wear process between spool and valve sleeve.

### 3.3 Fatigue wear

Surfaces can wear by fatigue when they are subject to fluctuating loads. High surface stresses cause cracks to spread into the material, and when two or more



**Figure 3.**  
*Adhesive wear in industries.*



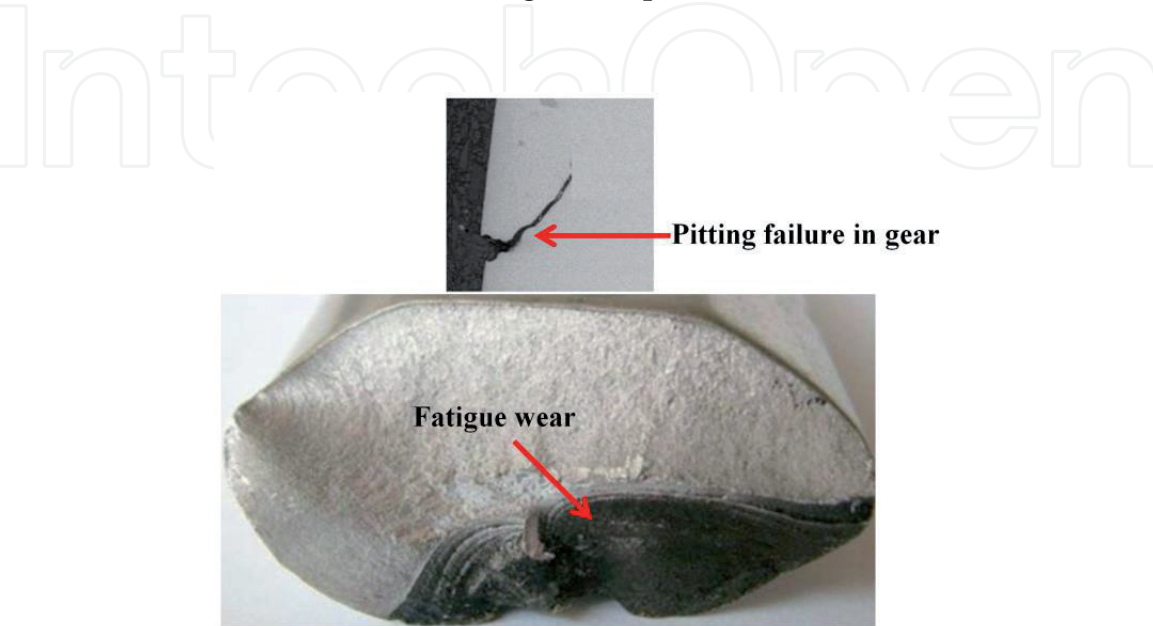
**Figure 4.**  
*SEM morphology of adhesive wear surface of spool shoulder [3].*

of these cracks become joined together large loose particles are formed. Thermal Surface Fatigue occurs when high repetitive stresses are generated through the heating caused by the contact of the two contacting components which result in cracking of the surface and the loss of small chunks of material. Surface fatigue is a cycle where the outside of a material is debilitated by cyclic stressing, which is one sort of broad material weariness (**Figure 5**). Fatigue wear is developed when the wear particles are confined by cyclic split development of microcracks on a superficial level. These microcracks are either shallow splits or subsurface breaks.

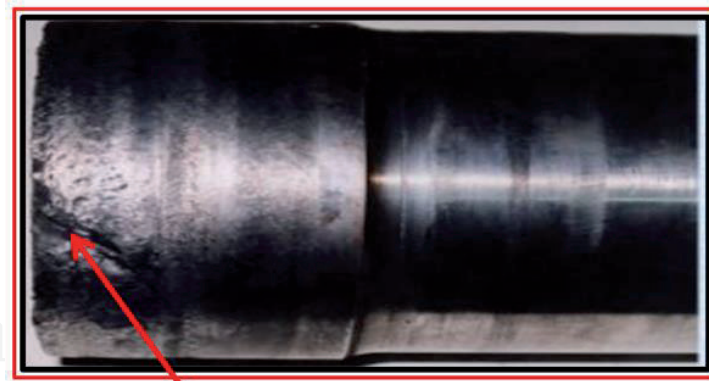
Mao et al. [4] investigated the fatigue wear phenomena of the gear and in his investigation he found out that the main reason of fatigue wear is the high stress concentration. The pitting failure due to the stress concentration is illustrated in **Figure 5**.

### 3.4 Fretting wear

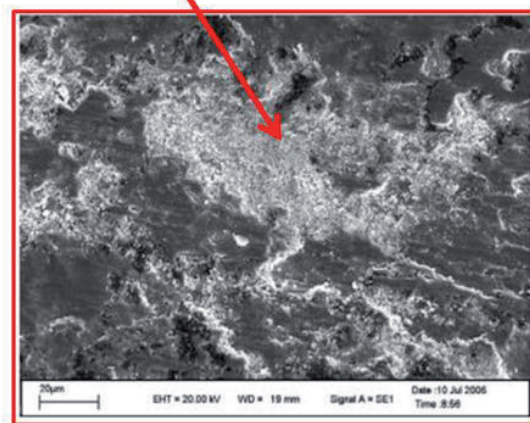
Fretting occurs where two contacting surfaces, often nominally at rest, undergo minute oscillatory tangential relative motion (**Figure 6**). Small particles of metal are removed from the surface and then oxidized. Typically occurs in bearings although the surfaces are hardened to compensate this problem and also can occur with cracks in the surface (fretting fatigue). This carries the higher risk of the two as can lead to failure of the bearings. Fretting wear is the rehashed recurrent scouring between two surfaces. Over some stretch of time fretting this will eliminate material from one or the two planes in contact. It happens normally in orientation, albeit most headers have their surfaces hardened to oppose the issue. Another issue happens when splits in either surface are made, known as fretting fatigue. It is the more genuine of the two marvels since it can prompt disastrous disappointment of the bearing. A related issue happens when the little particles eliminated by wear are oxidized in air. The oxides are generally harder than the fundamental metal, so wear quickens as the harder particles rub the metal surfaces further. Fretting corrosion acts similarly, particularly when water is available. Unprotected bearings on enormous structures like bridges can endure genuine debasement in conduct, particularly when salt is utilized during winter to deice the highways conveyed by the bridges. The issue of fretting corrosion was associated with the Silver Bridge misfortune and the Mianus River Bridge mishap.



**Figure 5.**  
*Fatigue and pitting wear in industrial parts.*



**Fretting wear**



**Figure 6.**  
*Fretting wear in industrial parts.*

Akhtar et al. [5] revealed in his research that the surface after 300 N testing have very heavy plowing of the steel matrix (**Figure 6**). At higher loads microplowing is very severe and causes the rapid removal of the material from the surface of the composite.

### 3.5 Erosive wear

Erosive wear is loss of material from a solid surface due to relative motion in contact with a fluid which contains solid particles impingement by a flow of sand, or collapsing vapor bubbles (**Figure 7**). Erosive wear closely depends on the material properties of the particles, such as hardness, impact velocity, shape and impingement angle. Example: A common example is the erosive wear associated with the movement of slurries through piping and pumping equipment. Erosive wear can be characterized as an amazingly short sliding movement and is executed inside a brief timeframe stretch. Erosive wear is brought about by the effect of particles of solid or fluid against the surface. The affecting particles steadily eliminate material from the surface through rehashed deformation and cutting mechanisms. It is a broadly experienced system in industry. Because of the idea of the passing on measure, funneling frameworks are inclined to wear when rough particles must be moved. The pace of erosive wear depends upon various elements. The material qualities of the particles, for example, their shape, hardness, impact speed and impingement edge are essential factors alongside the properties of the surface being disintegrated. The impingement point is one of the most significant factors. For ductile materials, the greatest wear rate



Gas turbine blade surface  
eroded by solid particle  
erosion wear



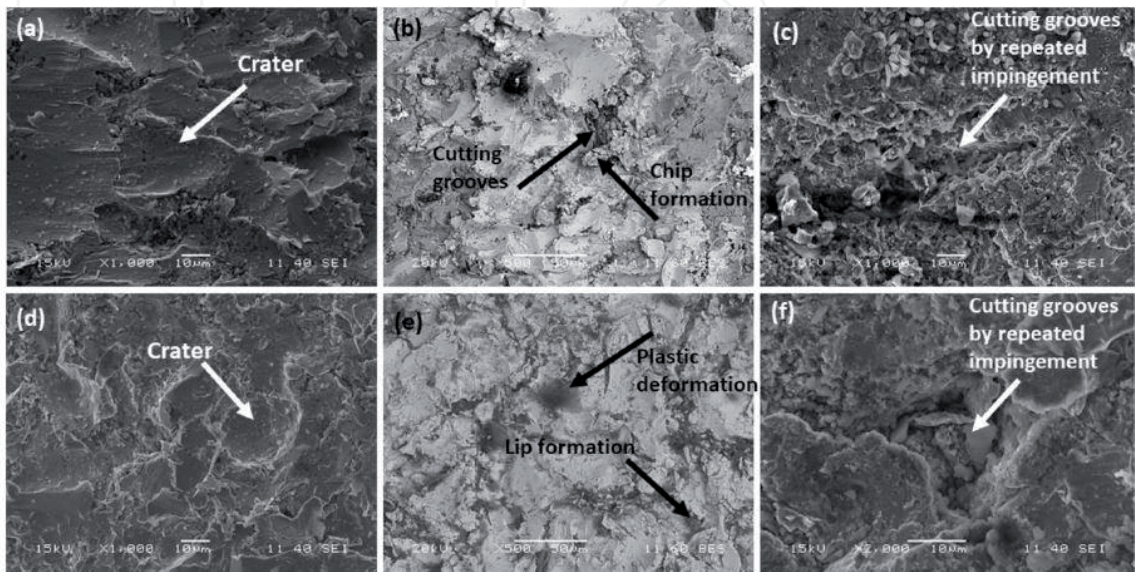
**Figure 7.**  
*Erosion of compressor blades in gas turbine engine.*

is discovered roughly at 30° impingement angle, while for brittle materials the most extreme wear rate happens when the impingement angle is normal to the surface.

Swain et al. [6] investigated about the erosion behavior of the plasma sprayed NITINOL coating. In this work, the surface was eroded by 45 and 90° impingement angle of erodent. The wear mechanisms can be observed from the **Figure 8**. The surface impinged at 45° impingement angle (**Figure 8(a)–(c)**) having crater formation, chip formation and cutting grooves mechanisms. Whereas, the eroded surface at 90° impingement angle (**Figure 8(d)–(f)**) having crater formation, plastic deformation and lip formation mechanisms.

**3.6 Corrosive and oxidation wear**

Corrosion and oxidation wear happens both in oily and dry contacts (**Figure 9**). The essential reason are chemical reactions between wear surface and the eroding medium. Wear brought about by a synergistic activity of tribological stresses and



**Figure 8.**  
*SEM morphologies of eroded surface at (a), (b), (c) 45° and (d), (e), (f) 90° impingement angle [6].*



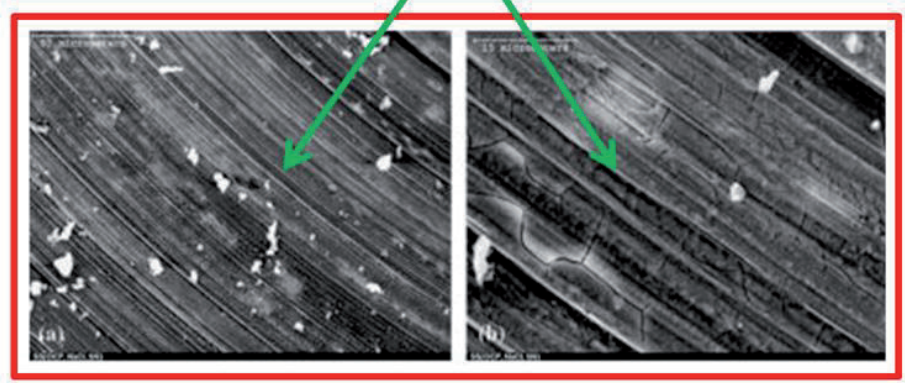
Surface damage due to corrosion and oxidation



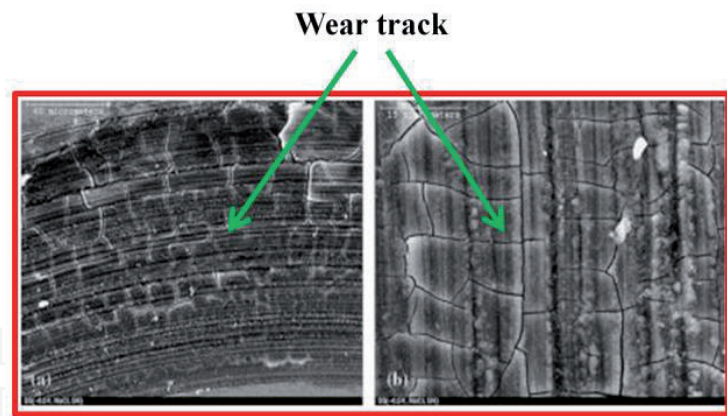
**Figure 9.**  
*Corrosive and oxidation wear of structural members of industries.*

consumption is likewise called tribocorrosion. Corrosive wear is otherwise called chemical wear. Corrosive wear is an assault on a material surface inside its condition. Corrosive wear can be either is wet or dry, contingent upon the sort of condition present for a specific response. Generally, wet erosion happens in an answer, for example, water, with some disintegrated species in it, which makes an acidic situation and response over the surface. Dry erosion is predominantly obstructed by the presence of dry gases, for example, characteristic air and nitrogen, etc. Since nature assumes an enormous function in corrosion wear, material choice is fundamental and ought to be the concentration before planning a segment. In erosion wear, corrosion and wear are two free instruments; if the demonstrations happen independently, the condition might be more basic than the consolidated impact of both. In presence of oil on a superficial level, consumption will be uniform all through the surface. On the off chance that limits of precious stone materials are defenseless to consumption rather than inside material, it is known as intergranular erosion. Pitting brought about by impingement of particles on the material surfaces produces pits and openings on the surfaces, which is difficult to perceive on a superficial level. Subsurface corrosion is disconnected particles that exist underneath the eroding material, essentially because of the response of constituents with the defused medium.

Wear track



**Figure 10.**  
*SEM images of the wear track on an unprotected sample in the NaCl solution: (a) wear track, (b) a closer view at the wear track.*



**Figure 11.** SEM images of the wear track on a cathodically protected ( $-0.50\text{ V}$ ) sample in the NaCl solution: (a) wear track, (b) a closer view at the wear track [7].

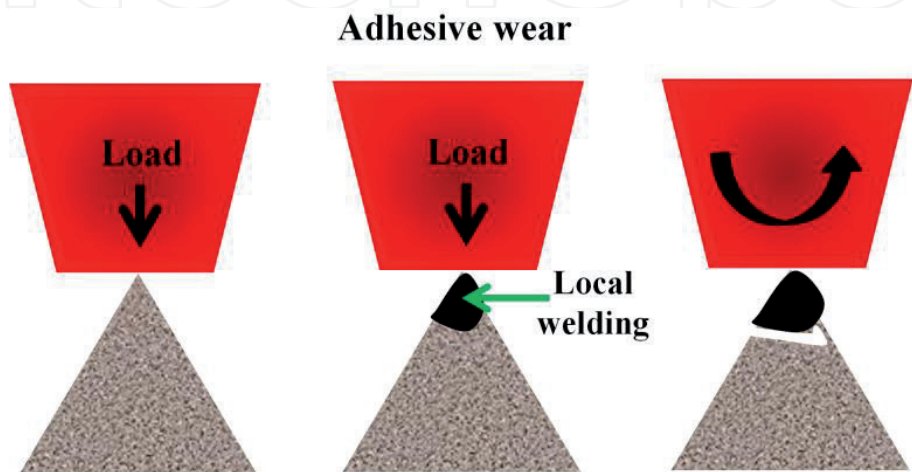
Akonko et al. [7] investigated the corrosive wear phenomena on both the protected and unprotected samples in the NaCl solution under a force of 5 N and found that the worn surface of a non-protected sample (**Figure 10**) indicated less cracks than those of cathodically protected (**Figure 11**). This indicates that the cathodic protection caused hydrogen embrittlement, and this has further boosted by stress, therefore caused more wear.

4. Wear mechanisms

4.1 Adhesive wear

The sort of mechanism (**Figure 12**) and the abundance of surface fascination fluctuates between various materials yet are enhanced by an expansion in the thickness of “surface energy”. Most solids will stick on contact somewhat. Nonetheless, oxidation films, oils and contaminants normally happening for the most part stifle attachment, and unconstrained exothermic chemical reactions between surfaces by and large produce a substance with low vitality status in the retained species.

Adhesive wear can prompt an expansion in harshness and the production of projections (i.e., protuberances) over the first surface. In modern assembling, this is alluded to as irking, which inevitably penetrates the oxidized surface layer and



**Figure 12.** Adhesive wear mechanism.

interfaces with the fundamental mass material, improving the opportunities for a more grounded bond and plastic flow around the knot.

A model for the wear volume for cement wear,  $V$ , can be portrayed by:

$$V = K \times WL / Hv$$

Where, ' $W$ ' represents load, ' $K$ ' is the wear coefficient, ' $L$ ' represents the sliding distance, and ' $Hv$ ' is the hardness.

#### 4.2 Abrasive wear

The system of material expulsion in abrasive wear is essentially equivalent to machining and grinding during an assembling cycle (**Figure 13**). At the beginning of wear, the hard severities or particles enter into the milder surface under the typical contact tension. The wear trash regularly has a type of micro cutting chips.

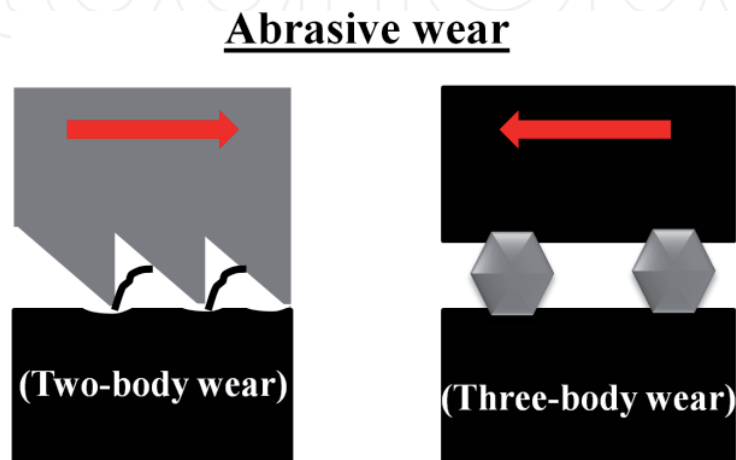
A few methods have been suggested to foresee the volume misfortune in abrasive wear. A least difficult one includes the scratching of materials by angular shaped hard particles (indenter). Under an applied heap of  $P$ , the hard molecule enters the material surface to a profundity of  $h$  which is straightly relative to the applied burden ( $P$ ) and conversely corresponding to the hardness ( $H$ ) of the surface being scraped. As sliding happens, the molecule will furrow (cut) the surface delivering a depression, with the material initially ready being eliminated as wear flotsam and jetsam. On the off chance that the sliding distance ( $L$ ) and the wear volume ( $V$ ) can be written as:

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

Here, ' $k$ ' is wear coefficient partially reflecting the effects of geometries, and properties of the particles (or asperities), and partly reflecting the influences of additional factors such as sliding speed, and lubrication environments.

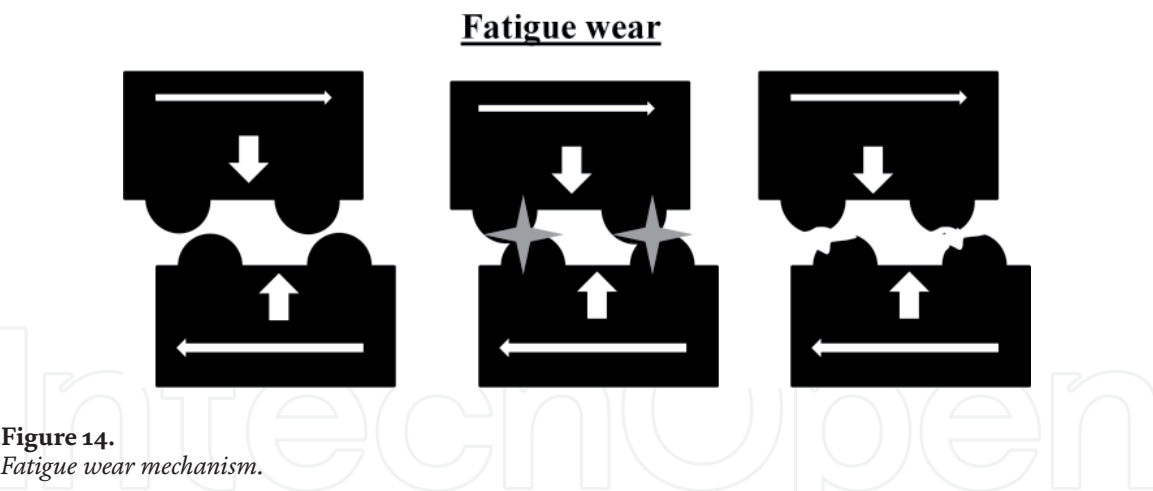
#### 4.3 Fatigue wear

Two mechanisms (**Figure 14**) of fatigue wear are recognized: high-and low-cycle fatigue. In high-cycle fatigue, the quantity of cycles before fatigue is high,



**Figure 13.**  
*Abrasive wear mechanism.*



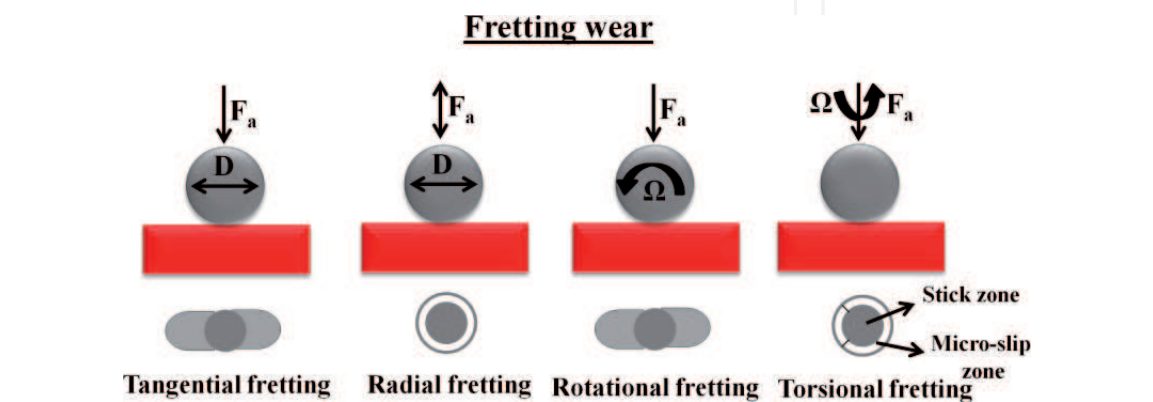


so the part life is generally long. The splits for this situation are created because of prior miniature imperfections in the material, near which the nearby pressure may surpass the yield esteem, despite the fact that ostensibly the naturally visible contact is in the flexible system. Gathering of plastic strain around inhomogeneities is an antecedent for commencement of a split. In the low-cycle fatigue, the quantity of cycles before disappointment is low, so the part bombs quick. In this mode, pliancy is prompted each cycle and the wear molecule is produced throughout aggregated cycles. The wear garbage is not produced at the principal cycles, yet just the shallow furrows because of plastic misshapening are framed, as talked about in. After a basic number of cycles, the plastic strain surpasses a basic worth and the crack happens. There are the three phases in break proliferation: split inception, development and post-basic stage, when the calamitous disappointment happens. The vast majority of the lifetime of the part is involved by the primary stage, with the spans of introductory splits around 2–3  $\mu\text{m}$  and lower.

**4.4 Fretting wear**

Cyclic motion between contacting surfaces is the essential ingredient in all types of fretting wear. It is a combination process that requires interaction of two surfaces, and exposed to minor amplitude of oscillations.

According to 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 (**Figure 15**) changes to three-body abrasion when the work-hardened debris starts removing metal from the surfaces.



**Figure 15.**  
*Fretting wear mechanism.*

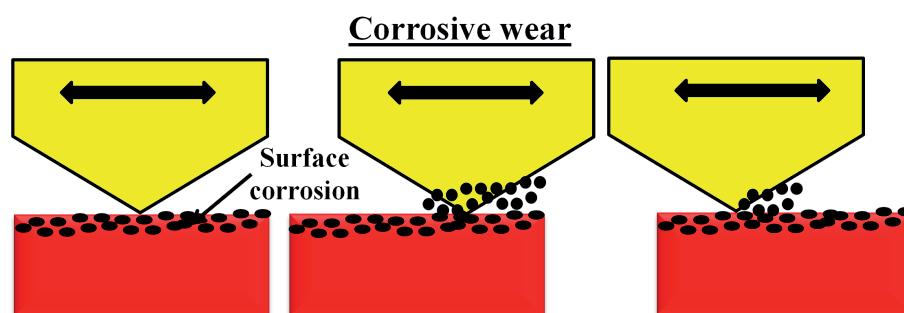
Fretting wear arises as a result of the following order of events:

- The normal load causes asperities to stick and the tangential oscillatory motion shaves the asperities and produces wear debris that stores.
- The surviving (harder) asperities eventually act on the smooth surfaces causing them to undergo plastic deformation, create voids, propagate cracks and shear off sheets of particles which also gather in depressed areas of the surfaces.
- Once the particles have accumulated sufficiently to span the gap among the surfaces, abrasion wear follows and the wear zone extents laterally.
- As adhesion, delamination, and abrasion wear lasts, wear debris can no longer be contained in the primary zone and it outflows into surrounding valleys.
- Because the maximum stress is at the center, the geometry becomes curved, micropits form and these coalesce into larger and deeper pits. Finally, depending on the displacement of the tangential motion, worm tracks or even big cracks can be produced in one or both surfaces.

#### 4.5 Corrosive and oxidation wear

Metal surface is normally covered with a layer of oxide, which could restrict metal-to-metal interaction, and therefore evading the development of adhesion and reducing the tendency of adhesive wear. In this connection, oxide is a favorable factor in reducing wear rate of metallic materials. However, whether such beneficial effect can be realized or not, is intensely reliant on the material properties and on contact conditions. When the hardness of the metal underlying an oxide layer is low, or when the contact load is relatively higher, the metal beneath the oxide layer will deform plastically, and asperities in the rigid surface will penetrate through the thin oxide layer, leading to the normal metal-to-metal contact. In such case, wear by abrasion or adhesion will occur depending on the mechanical properties and chemical properties of the contacting metals. The beneficial effect of oxide is minimal and wear rate is generally high. On the other hand, when the underlying metal is hard enough to support the oxide film, such as on a surface engineered hard surface, a process known as oxidation wear (**Figure 16**) will occur.

It needs to be mentioned that during sliding, the increased surface temperature promoted by frictional heating, and the less activation energy of oxide formation caused by plastic deformation, can increase the oxidation rate. Thus, rapid oxidation can be achieved, and the oxide layer can grow thicker during sliding than that



**Figure 16.**  
*Corrosive wear mechanism.*

under static conditions. This ensures the fresh metal is rapidly covered with a new layer of oxide after the original oxide film was worn away. Oxidation wear will not happen in vacuum or in inert atmosphere, since re-oxidation is not possible. Oxidation is a minor form of wear. When the predominant wear mechanism is changed from abrasive or adhesive to oxidation wear, degree of wear can be reduced by some orders of magnitude.

## **5. Use of surface coating for the protection from wear**

As wear is a surface or near surface phenomenon it has long been realized that the wear resistance of a component can be improved by providing a surface of different composition from the bulk material. After a brief introductory chapter wear phenomena and the properties required from a coating are addressed. Coating processes provide protection to a specific part or area of a structure exposed to harsh and corrosive environments in different fields ranging from aerospace and the automotive industry to tiny biomedical devices and implants inside the human body.

## **6. Types of surface coating**

### **6.1 Physical vapor deposition (PVD) coating**

PVD process is well-known for offering corrosion, wear resistance, and thin protective films on the surface of the materials that are exposed to corrosive media, and its applications range from decorative objects to industrial parts. The benefit of this technique is that the mechanical, corrosion, and esthetic properties of the coating layers could be adjusted on demand. Generally, PVD is a method that occurs in a high vacuum, and the solid/liquid materials transfer to a vapor phase followed by a metal vapor condensation, which creates a solid and thick film. The common types of PVD methods are sputtering and evaporation. Since the coating layers created by PVD are thin in nature, there is always a need for multilayered coatings while the materials selection should be considered carefully.

### **6.2 Chemical vapor deposition (CVD) coating**

Another type of vapor deposition is called CVD. This process undergoes a high vacuum and is widely used in the semiconductors industry providing a solid, high quality, and a high resistance coating layer on any substrate. CVD can be used for mechanical parts in continuous interaction, which need protection for corrosion and wear. In this method, the substrate, known as a wafer, would be exposed to a set of volatile material precursors where a chemical reaction creates a deposition layer on the surface of the material. However, some by products of these chemical reactions, which are removed by continuous airflow of the vacuum pump, can stay in the chamber.

### **6.3 Micro-arc oxidation (MAO) coating**

MAO method is known as a flexible method of coating concerning the composition of coatings. In general, MAO utilizes a high voltage difference between anode and cathode to generate micro-arcs as plasma channels. When these arcs hit the substrate, they melt a portion of the surface, depending on the intensity of the micro-arcs. Simultaneously, plasma networks discharge their pressure, which supports the



deposition of coating materials in the working electrolyte on the substrate surface. The existing oxygen in the electrolyte causes a chemical reaction resulting oxidation and the oxides gets deposited on the surface of the substrate. The adaptability of this process lies in the flexibility of combining preferred elements and compounds as a solute in the working electrolyte. With MAO, the most common substrate materials are Al, Mg, Ti, and their alloys.

#### **6.4 Electro deposition coating**

Electro deposition of materials is considered a type of protection utilizing the deposition of metallic ions on a coating substrate. In this method, a difference in potential between anode and cathode poles causes an ion transfer in the unit cell. After a while, a coating layer forms on the submerged sample by getting ions from the other electrode. The common group of metals that have been intensively studied includes, but is not limited to, Ni-P, Ag/Pd, Cu/Ag, Cu/Ni, and Co/Pt.

#### **6.5 Sol-gel coating**

Sol-gel synthesis is used to obtain coatings that can modify the surfaces of metals to avoid corrosion or to enhance the biocompatibility and bioactivity of metals and their alloys that are of biomedical interest. Anticorrosion coatings composed of smart coatings and self-healing coatings will be described.

#### **6.6 Thermal spray coating**

Thermal spray coating is a general term for a series of processes that utilize a plasma, electric, or chemical combustion heat source to melt a set of designed materials and spray the melt on the surface in order to produce a protective layer. These are reliable types of corrosion- and wear-resistant coatings. In this process, a heat source or plasma, heats up the coating materials to a fully molten or semi-molten phase and sprays them on the substrate material with a high velocity jet.

Thermal spraying dates back to the early 1900s when Dr. Schoop [1] first carried out experiments in which molten metal were atomized by a stream of high-pressure gas and propelled on to a surface. The Schoop process consisted of a crucible filled with molten metal while the propellant, hot compressed air, provided enough pressure to break up the molten metal, creating a spray jet. This system was quite rudimentary and inefficient. Following Schoop's work some improvements to the process were introduced. But the disadvantages of the process is that, it was only useful for low-melting-temperature metals, that the molten metal caused severe corrosion and that it was not possible to establish a continuous process, were enough to stop further progress.

Schoop then focused his efforts in another direction and in 1912 the first device for spraying metal wires was produced. The principle of this process is simple; a wire was fed into a combustion flame which melted the tip of the wire and then compressed air surrounding the flame atomized the molten metal and drove the tiny droplets on to a substrate to form a coating. In addition to improvements to nozzle and gun design along with the wire feed drive rolls, the basic principle of the process is the same today. This procedure is called flame spraying (FS) and covers an enormous group of thermal spray techniques which use powder, wires or rods.

A completely new concept in thermal spraying was introduced by Schoop in 1914 when he used electricity to melt the feedstock material. The most advanced equipment made by Schoop was quite similar to current electric arc spraying. This method is based on producing an electric arc among two wires of conducting

materials, which are fed together inside the gun. This arc is created at the tip of the wires and a jet of compressed air propels the molten metal to the substrate.

The concept of powder FS was introduced by F. Schori in the early 1930s, when a metallic powder was fed into a flame by the Venturi effect. The coating powder was heated in the nozzle and the exhaust gases (oxygen and acetylene) propelled the droplets. Improvements to the process incorporated in modern guns include an inert compressed gas that pressurizes the combustion chamber and results in rise in particle velocity.

The main problem associated with these early techniques was feedstock material. They all used a low-melting-point material, which leads to limited applications. Years passed, and the demand for high-temperature-resistant materials increased, until in the 1950s new systems that would boost the thermal spray market appeared. Firstly a modification of wire FS, the ceramic rod FS technique, which could use stabilized zirconias and aluminas appeared. However, it was the development, in about 1955, of the detonation gun (D-Gun) and atmospheric plasma spraying (APS) in about 1960 that proved to be the watershed as regards thermal spray applications.

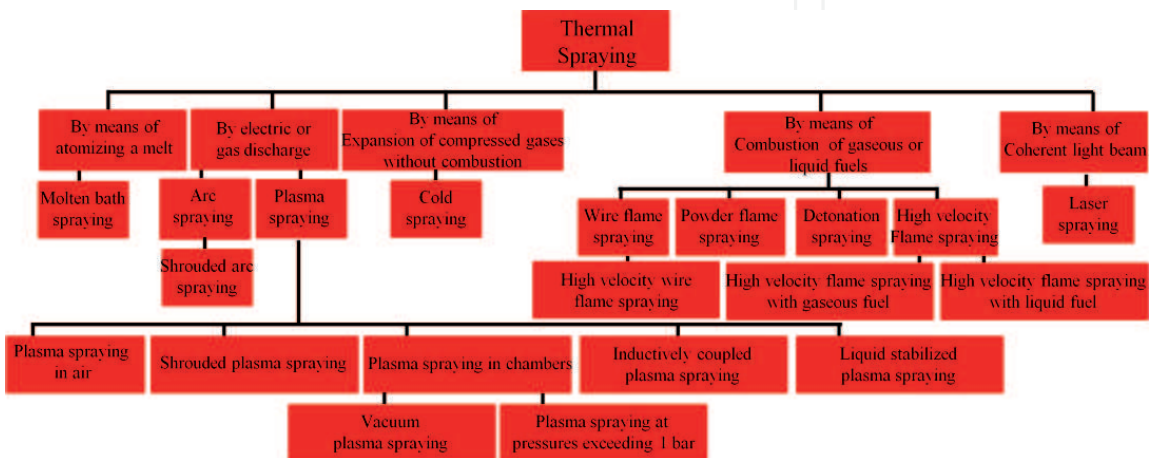
The thickness achieved in thermal spray coating techniques can range from 20 micron to several milli meters which are significantly higher than the thickness offered by electroplating, CVD, or PVD processes. In addition, the materials that can be used as feedstock of thermal spray coatings range from refractory metals and metallic alloys to ceramics, plastics, and composites and can easily cover a relatively high surface area of a substrate. Therefore the current chapter will mostly focus on this coating process.

## 7. Types of thermal spray processes

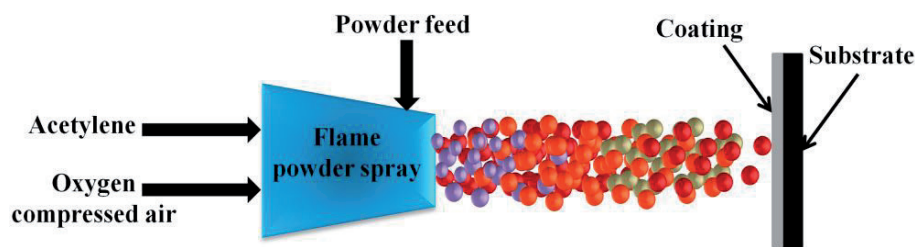
There are various types of thermal spray coating processes introduced by the researchers (**Figure 17**).

### 7.1 Powder flame spraying

In powder flame spraying, the feedstock material is injected to the plume for heating and melted by the heating zone. After melting the molten particles are propagated towards the substrate surface. Then the molten particles are deposited on the substrate surface or pre-deposited splat to form a coating (**Figure 18**). The molten particles are ejected by the flame spray gun. The only difference between powder flame spraying and wire flame spraying is the feedstock material.



**Figure 17.**  
*Classification of thermal spray coating process.*



**Figure 18.**  
*Powder flame spray technology.*

## 7.2 Wire or rod flame spraying

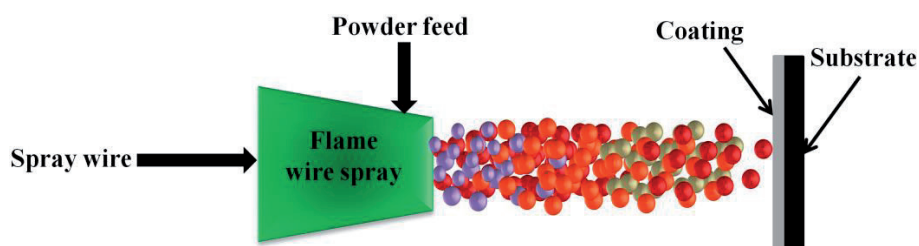
In rod type flame spray, the rod or wire is allowed to the heating zone where it melts and propagated by the plume towards the substrate to form coating (**Figure 19**). The feedstock rod may be a conventional rod or wire or manufactured by powder metallurgy process (sintering or binding). The melted particles are propelled towards the substrate, strike the surface at high velocity and flatten and form coating with a high adhesion strength with previously formed splat and substrate.

## 7.3 Detonation flame spraying

By the term “detonation” is meant a very rapid combustion in which the flame front moves at velocities higher than the velocity of sound in the unburned gases, and therefore characterized as supersonic velocities. A precisely measured quantity of the combustion mixture consisting of oxygen and acetylene is fed through a tubular barrel closed at one end. In order to prevent the possible back firing a blanket of nitrogen gas is allowed to cover the gas inlets. Simultaneously, a predetermined quantity of the coating powder is injected into the combustion chamber. The gas mixture inside the chamber is ignited by a simple spark plug. The gas mixture combustion generates plume which melt the particles to form coating (**Figure 20**).

## 7.4 High velocity oxy-fuel spraying

High velocity powder flame spraying was developed about 1981 and comprises a continuous combustion procedure that produces exit gas velocities estimated to be 4000–5000 feet per second. This is accomplished by burning a fuel gas (usually propylene) with oxygen under high pressure (60–90 psi) in an internal combustion chamber. Hot exhaust gases are discharged from the combustion chamber through exhaust ports and thereafter expanded into an extending nozzle. Powder is fed axially into this nozzle and confined by the exhaust gas stream until it exits in a thin high speed jet to produce coatings which are much denser than those produced with conventional or standard powder flame spraying techniques (**Figure 21**).



**Figure 19.**  
*Flame wire spray technology.*



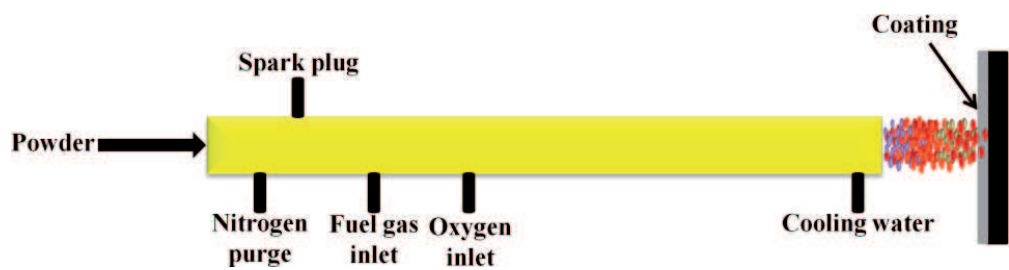


Figure 20.  
Detonation flame spray technology.

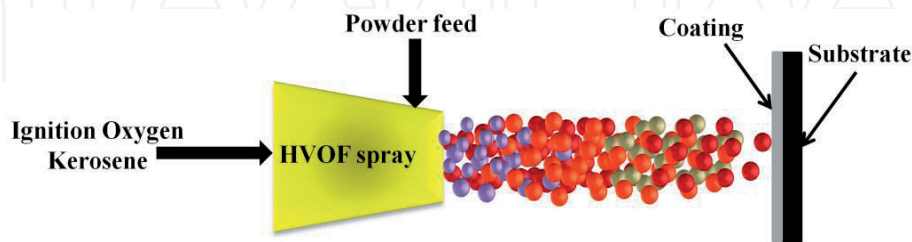


Figure 21.  
HVOF spray technology.

7.5 Wire arc spraying

Twin wire arc spraying is the most economical thermal spraying process. In this type of spraying process the heating and melting occur when two oppositely charged wires are fed together in a way that arc is generated at their intersection (Figure 22). Once struck, the arc continuously melts the wires, and compressed air blown directly behind the point of contact, atomizes and projects the molten droplets, which sticks to the substrate to form a coating. Arc fluctuations due to periodic removal of molten droplets from the electrode tips have strong effects on melting and coating properties such as porosity, microstructure and oxide content.

7.6 Plasma spraying process

Plasma spraying is a flexible and low-cost method to manufacture coating and bulk materials. The first idea of a plasma spray process was patented in 1909 in Germany, and the first structural plasma installation appeared in the 1960's, as the product of two American companies Plasmadyne and Union Carbide. A gas, usually argon, but occasionally including nitrogen, hydrogen, or helium, is allowed to flow between a tungsten cathode and a water-cooled copper anode. The cathode is placed in the cylindrical nozzle and the cylindrical nozzle is the anode. An electric arc is initiated between the two electrodes using a high frequency discharge and then

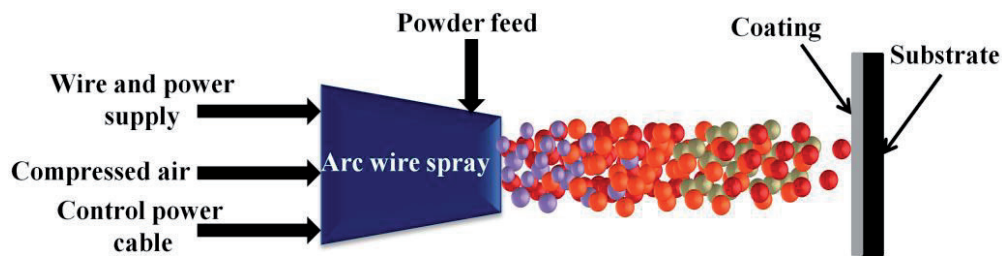
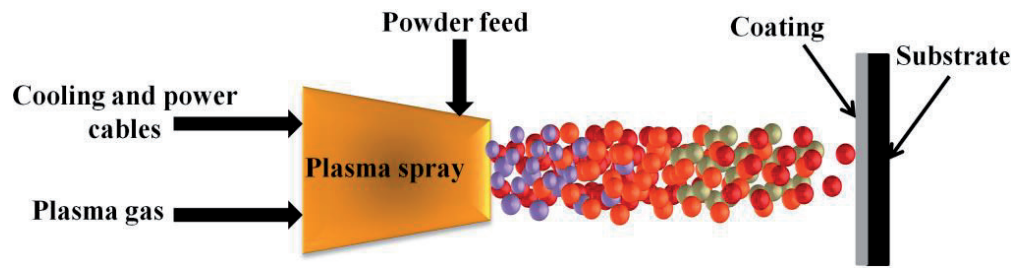


Figure 22.  
Wire arc spray technology.



**Figure 23.**  
*Plasma spray coating technology.*

sustained using dc power. The plasma is generated by the ionization of gas by the arc. The feedstock materials injected through the gun nozzle into the plasma plume, where it is melted and propagated to the substrates (**Figure 23**) [2, 6, 8–12].

## 8. Application of thermal spray technology for the protection from wear

A large range of industrial parts get advantage from thermal spraying, whether it is a portion of the manufacturing processes or as reclamations or re-engineering techniques. Some materials are used for minute role applications and others are sprayed by the tonne. Every application utilizes an amalgamation of procedure and material to give in the desired profit.

Reclamation and re-engineering of a wide range of rotating and moving parts from machines of all kinds, including: vehicles of both railways and highways, ships, aerospace, printing industries, paper industries, chemical industries, food industries, mining, earthmovers, machine tools, landing gear (chrome replacement) and any apparatus which is subject to wear, erosion or corrosion. This is done using either arc spray, flame spray or HVOF systems to spray steels, nickel alloys, carbides, stainless alloys, bronzes, copper and many other materials. New components which benefit from the enhanced surface properties that thermal spraying provides, include: Gate and ball valves, rock drilling bits, and down hole tools, print rollers, fluid seals, aerospace combustion chambers, turbine blades. Thermal sprayed coatings are used on a vast range of components which operate in harsh surroundings where, erosion, wear, corrosion or high temperature reduce part life. Part life is significantly prolonged due to thermal spray processes.

## 9. Conclusions

- Wear kinds of adhesive, abrasive, fatigue, and tribochemical wear are presented and their wear instruments are clarified with wear models in this chapter. In real wear of triboelements, a portion of these wear types are included simultaneously, and significant wear type changes at times starting with one then onto the next during running because of wear itself.
- Then again, wear is delicate to the difference in different framework boundaries, for example, mass, shape, stiffness, material properties, and condition. In light of such multiparameter affectability of wear, quantitative expectation of wear rate is still a long way from the real world.
- It gets significant, thusly, to perceive the significant wear type and its ordinary wear mechanisms according to framework boundaries.

- Surface covering improves the life of the segment and lessens the expense of substitution. The motivation behind surface innovation is to deliver practically compelling surfaces. A wide scope of coatings can improve the consumption, disintegration and wear obstruction of materials.
- We can reason that thermal spray coating is one of the most significant strategies of the surface change strategy. This examination was a push to give essential data with respect to a portion of the fundamental thermal spray strategies among which HVOF covering measure is most appropriate.
- By utilizing HVOF spray method uniform covering thickness, nonstop layer of covering and high hardness can be acquired. It has more favorable circumstances over the high quality, hardness, porosity, wear and erosion when contrasted with different cycle.

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