CHAPTER 1

SURFACE ENGINEERING AND WEAR

1.1 INTRODUCTION

Serviceable engineering components not only rely on their bulk material properties but also on the design and characteristics of their surface. This is especially true in wear resistant components, as their surface must perform many engineering functions in a variety of complex environments. The behaviour of a material is therefore greatly dependent on the surface of a material, surface contact area and the environment under which the material must operate. The surface of a metallic material is made up of a matrix of individual grains, which vary in size and bond strength depending on the means by which the material was manufactured and on the elements used to form those grains.

The surface of these components may require treatment, to enhance the surface characteristics. Surface treatments that cause microstructure changes in the bulk material include heating and cooling/quenching through induction, flame, laser, and electron beam techniques, or mechanical treatments (one example is cold working). Surface treatments that alter the chemistry of a surface include carburizing, nitriding, carbonitriding, nitrocarburizing, boriding, siliconizing, chromizing and aluminising (Bhushan and Gupta, 1991).

Hard facing is another form of surface treatment, where the bulk material's surface is given a protective layer of another material having more superior properties than those of the bulk material. An example of this is coating a turbine pump seal joint with a corrosive resistive material, to prevent salty water from eroding the pump. Each method of hard facing, examples of which are coating deposition, cladding or welding, causes particular physical and chemical effects on the bulk material, some beneficial, some detrimental. For example stresses which may exist in the protective material can create problems, however careful monitoring and research may limit these effects, to hopefully produce quality, serviceable engineering components. The following sections will describe the concept of surface engineering and the effects engineering environments have on these surfaces. Hard facing techniques are described in detail especially with regard to coating deposition technologies, with particular emphasis on thermal spray techniques, including the HVOF (High Velocity Oxy-Fuel) process, that used in the current research.

1.2 SURFACE ENGINEERING

The surface characteristics of engineering materials have a significant effect on the serviceability and life of a component, thus cannot be neglected in design. As described by Halling (1985), "Surface engineering can be defined as the branch of science that deals with methods for achieving the desired surface requirements and their behaviour in service for engineering components". The surface of any component may be selected on the basis of texture and colour, but engineering components generally demand a lot more than this. Engineering components must perform certain functions completely and effectively, under various conditions in aggressive environments.

Engineering environments are normally complex, combining loading with chemical and physical degradation to the surface of the component. Surface wear damage is a phenomenon which effects how a component will last in service. An example of a component working in an aggressive environment is a cutting tool used in machining processes. The tool experiences high loads, high speeds and friction and, as a consequence, high temperatures: These factors lead to surface wear of the component. Lubrication in tribological applications reduces friction and wear, however conventional liquid lubricants fail under extreme conditions, namely low pressure, oxidative or corrosive environments, high speeds and high loads. Surface coatings can help deal with these circumstances. Improving the tool surface, not only improves the life of the tool, but also improves the surface finish of the machined part. Obviously it is important to understand the physical and chemical make up of the applied surfaces, in order to design quality components which yield high service lives.

1.2.1 Solid Surfaces

A metal may look clean and polished, however the surface microlayers as shown in figure 1.1, have been formed due to external factors including machining, temperature and oxide formation. Depending on the manufacturing process involved in producing a material, a zone of work-hardened material will occupy the base of these additional layers. Above this worked layer is an amorphous or microcrystalline structure, called the 'Beilby' layer, which is a result of melting and surface flow during machining of the molecular layers. An oxide layer sits on top of the Beilbly layer, due to the oxygen available from the external environment, and surface oxidation mechanisms. A layer of adsorbates occupies the outer region and this is made up of water vapour or hydrocarbons from the environment that may have condensed and physically or chemically adsorbed onto the surface.

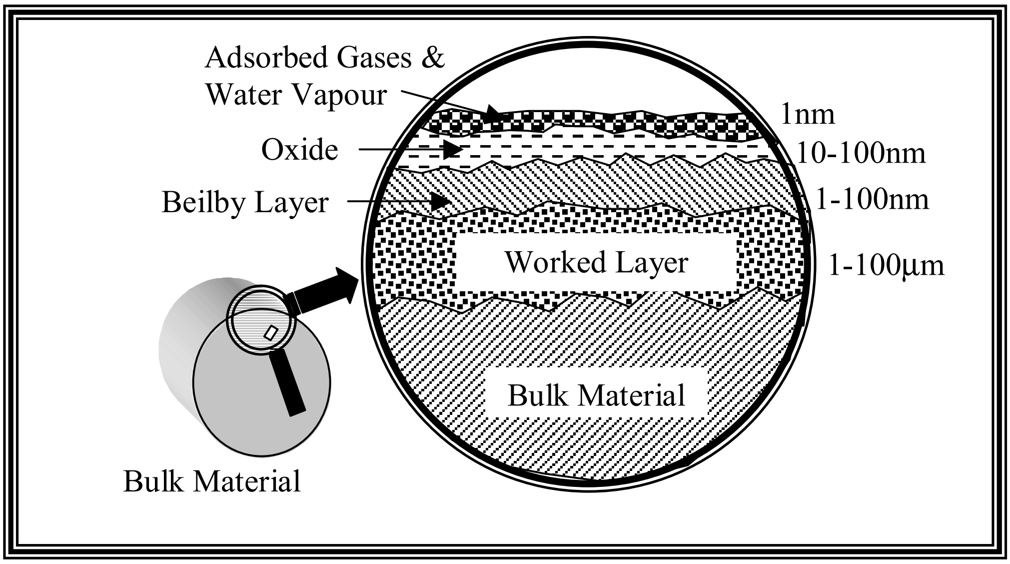

Figure 1.1, Schematic representation of a metal surface, adapted from Bhushan and Gupta (1991)

The surface shape or topology depends upon the process used for forming, be it moulding, casting, or cutting and abrading. As shown in figure 1.2 this is often seen microscopically as a series of asperities rather than the flat surface seen macroscopically. The geometrical texture may be characterized by its surface profile as shown in figure 1.3, and results from three different components of surface texture (roughness, waviness and error of form).

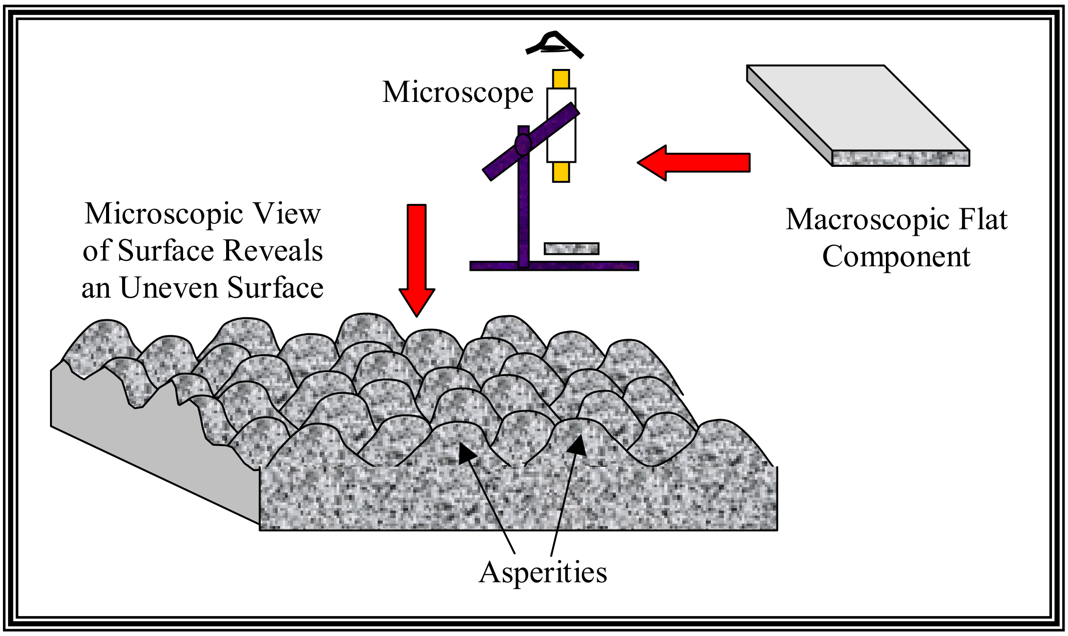

Figure 1.2, Surface asperities of a nominal smooth surface.

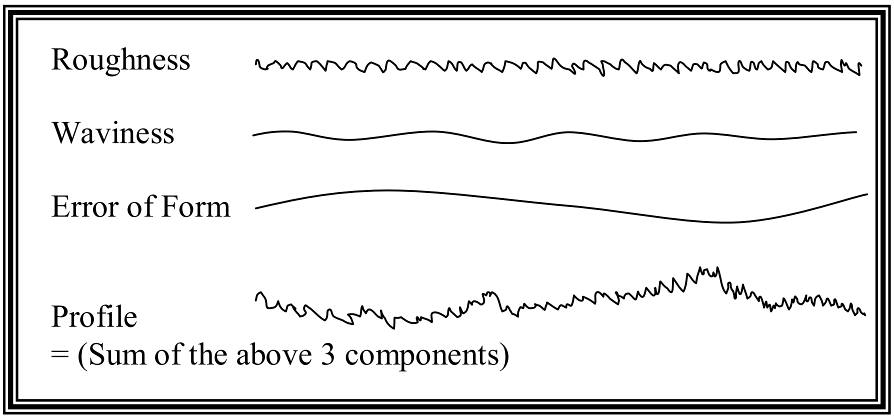

Figure 1.3, Three components of surface texture.

1.2.2 Friction And Wear

Friction and wear occur where two surfaces undergo sliding or rolling under load. Friction is a serious cause of energy dissipation, where wear is the main cause of material wastage. Suitable materials are selected for mating bodies and/or solid/liquid lubrication, is used to control friction and hence reduce the wear rate at which the mating surface degrades. In order to make the best choice of material for certain conditions, a deeper understanding of these two processes (friction and wear) is necessary.

Friction is the resistance to relative motion of contacting bodies. The degree of friction is expressed as a coefficient of friction μ, which is expressed as the ratio of force required to initiate or sustain relative motion, to the normal force that presses the two bodies together. Two modes of friction may occur; sliding or rolling friction. The friction between sliding surfaces (*sliding friction*) is due to the combined effects of adhesion between flat surfaces, ploughing by wear particles and hard asperities, and asperity deformation. Rolling friction is a complex phenomenon because of its dependence on so many factors, including inconsistent sliding (called *slip*) during rolling, and energy losses during mixed elastic and plastic deformations. Rolling friction may be classified into two types, one in which large tangential forces are transmitted (one example, the traction drives and driving wheels of an automobile), and another in which small tangential forces are transmitted, often referred to as *free rolling*.

Wear is a process of removal of material from one or both of two solid surfaces in solid state contact, occurring when two solid surfaces are in sliding or rolling motion together according to Bhushan and Gupta (1991). The rate of removal is generally slow, but steady and continuous. Figure 1.4 shows the five main categories of wear and the specific wear mechanisms that occur in each category. Each specific mode of wear looks different to the next, and may be distinguished relatively easily.

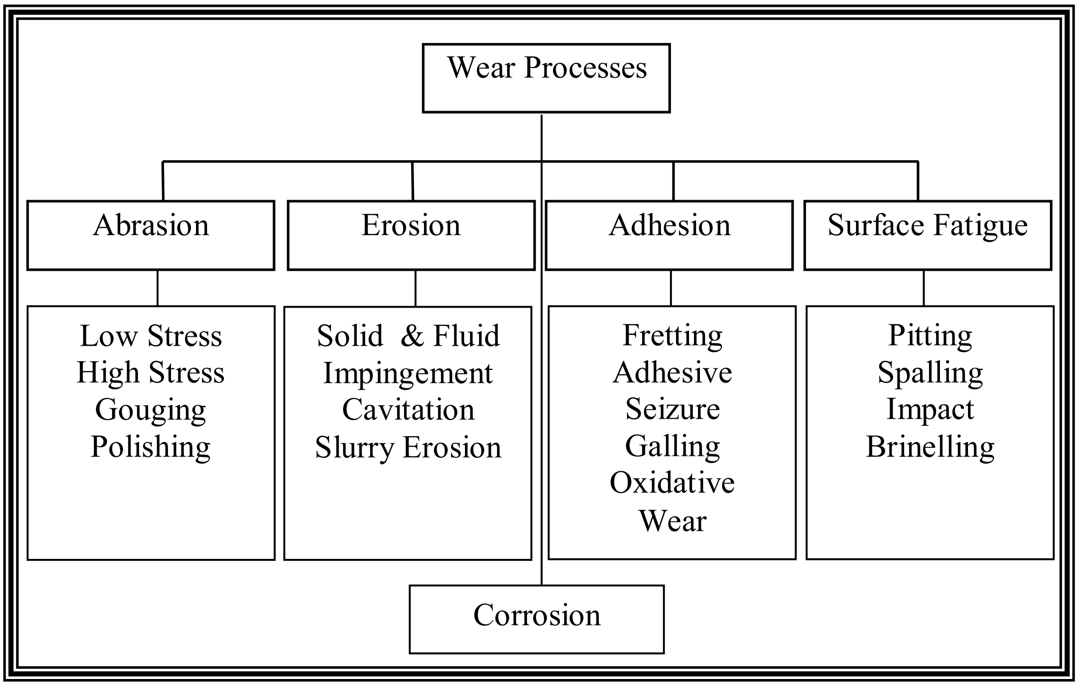

Figure 1.4, Flow chart of various wear mechanisms.

(1) Abrasive Wear

Abrasive wear occurs when material is removed from one surface by another harder material, leaving hard particles of debris between the two surfaces. It can also be called scratching, gouging or scoring depending on the severity of wear. Abrasive wear occurs under two conditions:

1. Two body abrasion; In this condition, one surface is harder than the other rubbing surface as shown in figure 1.5(a). Examples in mechanical operations are grinding, cutting, and machining.

2. Three body abrasion; In this case a third body, generally a small particle of grit or abrasive, lodges between the two softer rubbing surfaces, abrades one or both of these surfaces, as shown in figure 1.5(b).

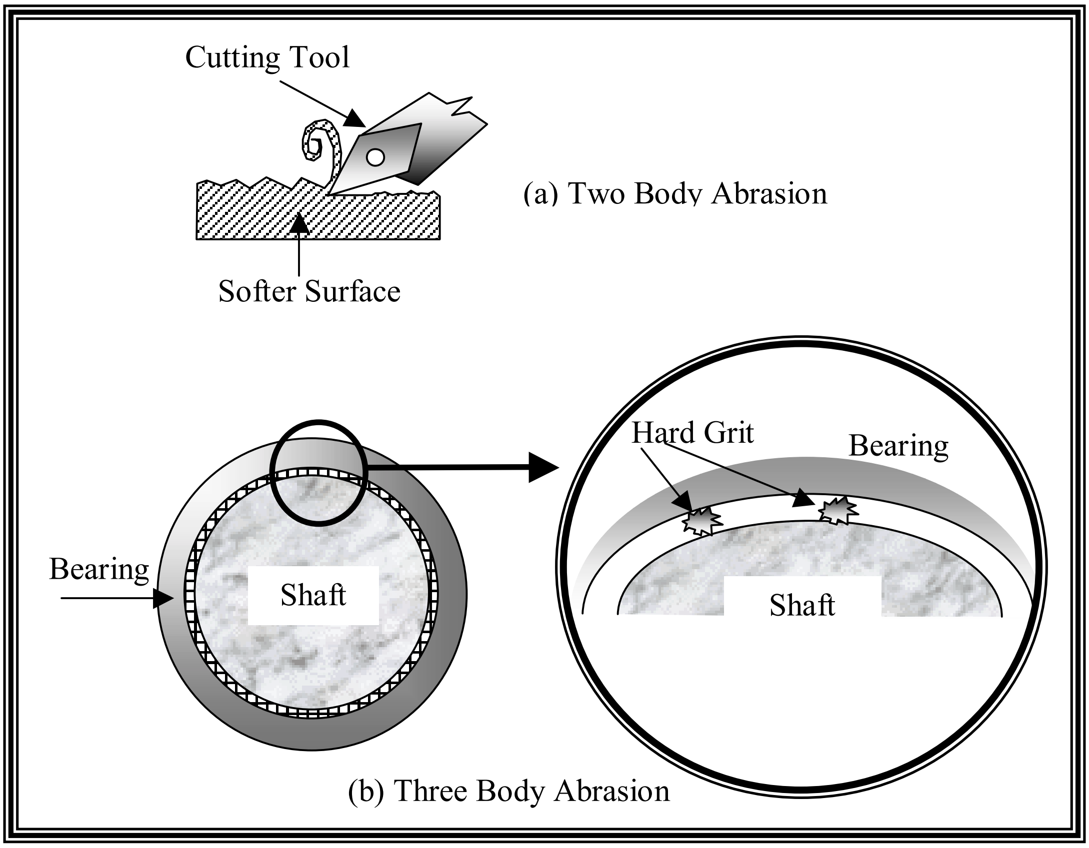

Figure 1.5, Schematic of abrasive wear phenomena.

In the microscale, the abrasive wear process is where asperities of the harder surface press into the softer surface, with plastic flow of the softer surface occurring around the harder asperities, as shown in figure 1.6. This often leads to what is known as microploughing, microcutting, and microcracking, when a tangential motion is imposed. Abrasive wear may be reduced by the introduction of hydrodynamic or elastohydrodynamic lubricants at various film thickness to separate the surfaces and to 'wash out' any contaminant particles. Research has shown that using the correct coating material and various thermally sprayed techniques including the HVOF process, greatly benefits resistance to abrasive wear (Scholl and Clayton, 1991; Mutasim and Hsu, 1994; Niemi et al., 1992; Bozzi and De Mello, 1999; Jacobs et al., 1999).

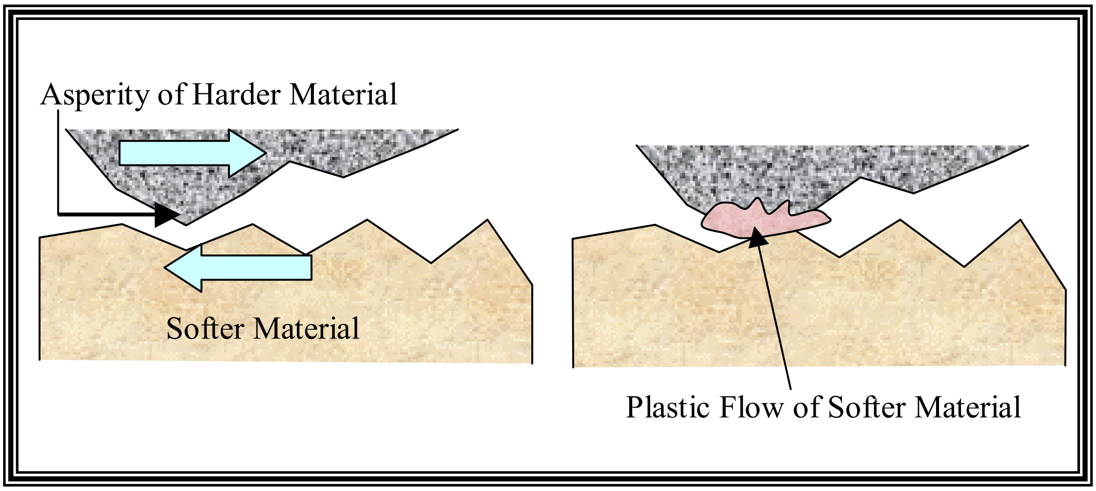

Figure 1.6, Abrasion in the microscale.

(2) Erosive Wear

The impingement of solid particles, or small drops of liquid or gas often cause what is known as erosion of materials and components. Solid particle impact erosion has been receiving increasing attention especially in the aerospace industry (Wang et al., 1992). Examples include the ingestion of sand and erosion of jet engines and of helicopter blades. As shown in figure 1.7 the erosion mechanism is simple. Solid particle erosion is a result of the impact of a solid particle A, with the solid surface B, resulting in part of the surface B been removed. The impinging particle may vary in composition as well as in form. The response of engineering materials to the impingement of solid particles or liquid drops varies greatly depending on the class of material, materials properties (dependant on thermal history, exposure to previous stresses or surface tensions), and the environmental parameters associated with the erosion process, such as impact velocity, impact angle, and particle size / type. Movement of the particle stream relative to the surface and angle of impingement both have a significant effect on the rate of material removal, according to D'Errico et al. (1999). The erosive effects on materials at high temperatures is important for the selection of turbine engine materials in the aerospace industry, according to Tu et al. (1991).

Cavitation erosion occurs when a solid and a fluid are in relative motion, due to the fluid becoming unstable and bubbling up and imploding against the surface of the solid, as shown in figure 1.8. Cavitation damage generally occurs in such fluid-handling machines as marine propellors, hydrofoils, dam slipways, gates, and all other hydraulic turbines, according to Bhushan and Gupta (1991). Cavitation erosion roughens a surface much like an etchant would.

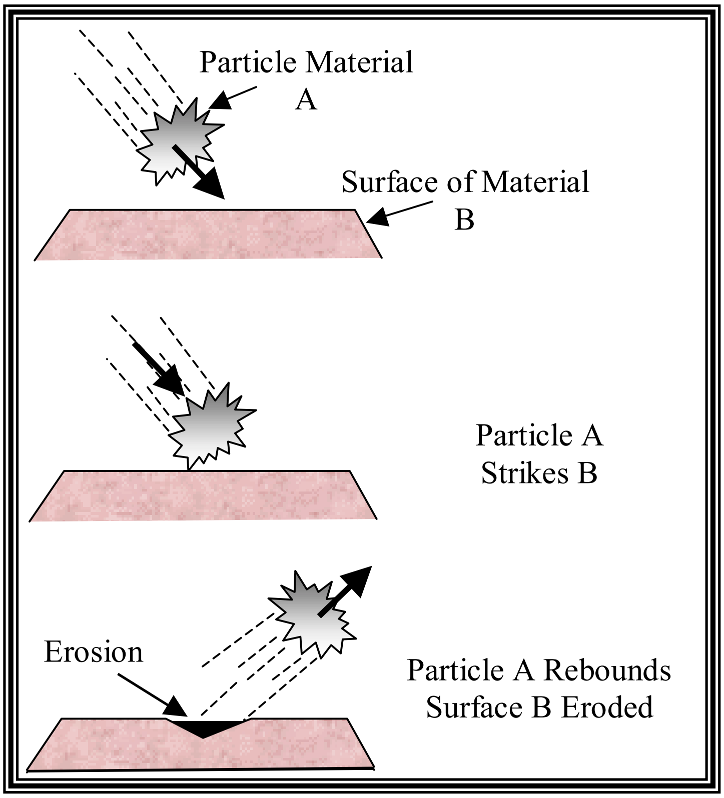

Figure 1.7, Schematic of erosive wear.

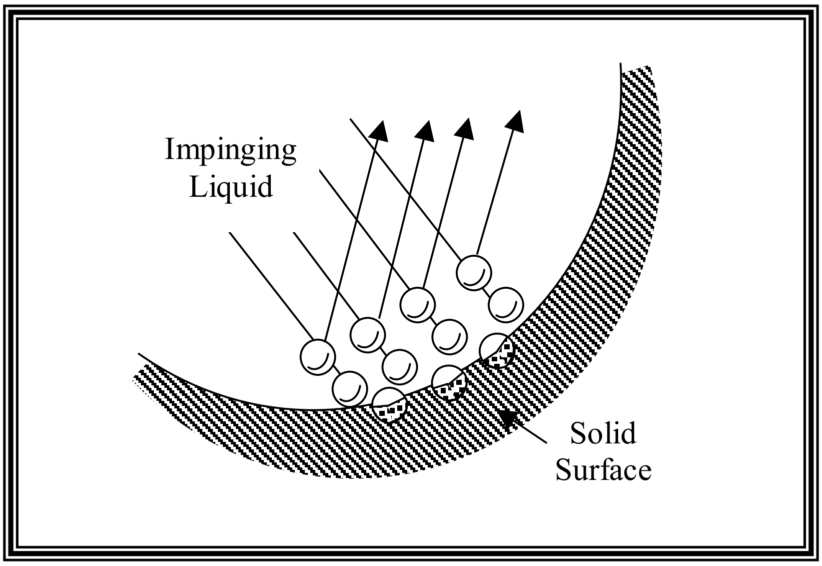

Figure 1.8, Schematic of cavitation erosion due to impingement of liquid bubbles.

(3) Adhesive Wear

Adhesive wear is often called galling or scuffing, where interfacial adhesive junctions lock together as two surfaces slide across each other under pressure, according to Bhushan and Gupta (1991). As normal pressure is applied, local pressure at the asperities become extremely high. Often the yield stress is exceeded, and the asperities deform plastically until the real area of contact has increased sufficiently to support the applied load, as shown in figure 1.9. In the absence of lubricants, asperities cold-weld together or else junctions shear and form new junctions. This wear mechanism not only destroys the sliding surfaces, but the generation of wear particles which cause cavitation and can lead to the failure of the component. An adequate supply of lubricant resolves the adhesive wear problem occurring between two sliding surfaces.

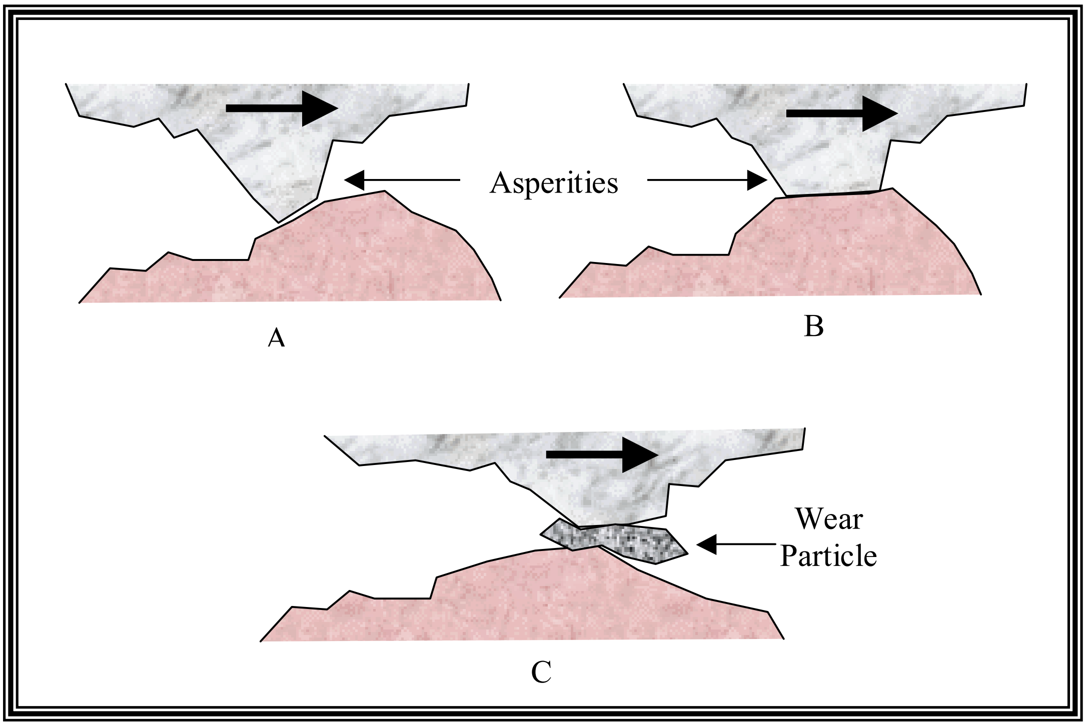

Figure 1.9, Schematic of generation of a wear particle as a result of adhesive wear process.

(4) Surface Fatigue

When mechanical machinery move in periodical motion, stresses to the metal surfaces occur, often leading to the fatigue of a material. All repeating stresses in a rolling or sliding contact can give rise to fatigue failure. These effects are mainly based on the action of stresses in or below the surfaces, without the need of direct physical contact of the surfaces under consideration. When two surfaces slide across each other, the maximum shear stress lies some distance below the surface, causing microcracks, which lead to failure of the component. These cracks initiate from the point where the shear stress is maximum, and propagate to the surface as shown in figure 1.10. Materials are rarely perfect, hence the exact position of ultimate failure is influenced by inclusions, porosity, microcracks and other factors. Fatigue failure requires a given number of stress cycles and often predominates after a component has been in service for a long period of time.

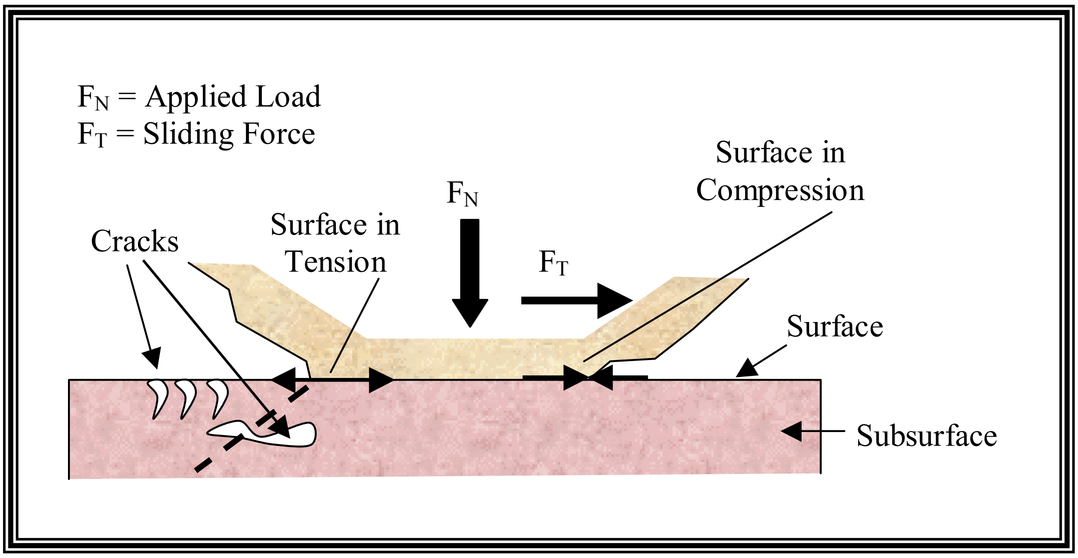

Figure 1.10, Schematic of fatigue wear, due to the formation of surface and subsurface cracks.

(5) Corrosive Wear

In corrosive wear, the dynamic interaction between the environment and mating material surfaces play a significant role, whereas the wear due to abrasion, adhesion and fatigue can be explained in terms of stress interactions and deformation properties of the mating surfaces. In corrosive wear firstly the connecting surfaces react with the environment and reaction products are formed on the surface asperities. Attrition of the reaction products then occurs as a result of crack formation, and/or abrasion, in the contact interactions of the materials. This process results in increased reactivity of the asperities due to increased temperature and changes in the asperity mechanical properties. Thermally sprayed coatings applied to various material surfaces, such as those depositing using the HVOF process, have proved an effective tool in the prevention of corrosion (Natishan et al., 2000).

1.2.3 Surface Protection

Much tribological research, involves the minimization of friction and wear experienced by materials in service. Effective lubrication between moving surfaces considerably reduces friction and therefore wear. Another approach is to surface harden components.

Ando et al. (2000), found that nitriding steel with an ammonia and nitrogen-hydrogen flame mixture, causes an increase in surface hardness. Diffusion methods such as carburizing, carbonitriding, nitrocarburizing, boriding and aluminizing, are also used to harden materials, however this process is time consuming (Bhushan and Gupta, 1991).

A variety of bulk materials, (ferrous and non-ferrous metals, alloys, ceramics and cermets), can be modified by alloying, mixing, compositing, and coating to achieve adequate resistance to wear corrosion and friction. Ceramics and cermets appear to be ideal wear-resistant materials, and suit many tribological applications provided that their strength and toughness are acceptable. Coating less wear resistive component materials with that of a high resistive material, offers an ideal method of surface protection.