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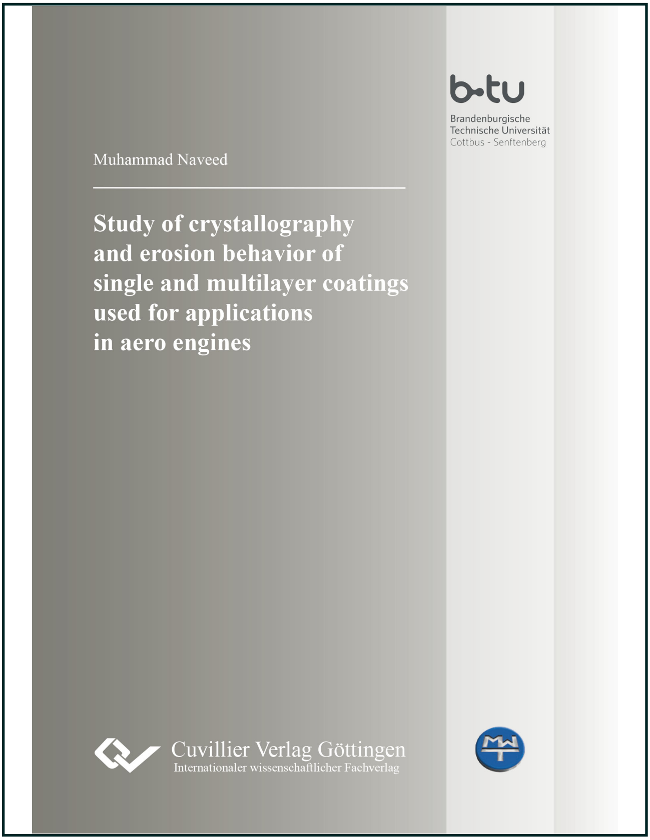
Study of crystallography and erosion behavior of single and multilayer coatings used for applications in aero engines



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1. Introduction

With the increasing number of commercial and military flights, air-based gas turbine manufacturers are looking for suitable methodologies to improve the efficiency of the engines working. Many of the material related problems like fretting of components, corrosion, oxidation, bio-fouling etc. [1, 2] are generally encountered in the aero engines. One of the main problems encountered by the military engines due to their operation in dusty environment is the Solid Particle Erosion (SPE). This problem has been reported mainly for the helicopters and military airplanes operating in dusty environments. Literature reports that dust erosion proved to be a severe problem during the Vietnam War where engines have to be removed after 100 hours of operation. Even after two decades of technological advances, many of the helicopter engines have to be removed after 20 hours of operation during the Gulf War [3]. The particle erosion leads to the wear of components and hence lead to decrease of engine efficiency and inefficient use of fuel. The replacement of worn components also leads to increase in overhaul costs for the turbine manufacturers. Hence, heavy investments have been made in order to produce efficient filters but still very small particles are still able to enter the engine and erode the components [4].

Figure 1.1: Landing of aircrafts in dusty environments leading to erosion of components (Reference: Airbus)

A conventional method to reduce component wear is the use of erosion resistant coatings. Such coatings should bear high hardness along with high fracture toughness in order to absorb energy of the incoming erodent before plastic deformation takes place. Literature indicates a number of single layer coatings like TiN, ZrN [5], TiAlN and multilayer coatings like Ti/TiN [5, 6], Ti/TiC [5], W/WN [7], Ti/TiB_2 [8] as possible coatings systems against erosion.

A traditional way to deposit such type of coatings is the conventional Direct Current (DC) method which finds its roots in Physical Vapor Deposition (PVD) methods. By employing this method a high deposition rate along with defect free structure is observed for the coatings. Moreover, the process is regarded to be economical and user friendly in comparison to other PVD methods as no complicated electronic devices are used in order to achieve high density plasma or to direct the electrons towards the surface.

The aim of this work is to study the behavior of single layer ceramic coatings and multilayer metal-ceramic coatings deposited through DC method. In order to deposit a multilayer coating with a metallic and ceramic layer, a study of the properties of the individual layers is necessary to select the best performing coatings. A combination of the best performing layers would allow achieving a multilayer coating with required properties. The first part of the work focus on the properties of the materials used for the deposition of coatings. Mechanical properties like Hardness and E-Modulus, coating growth rate, coating structure etc. of the coatings have studied to provide a correlation of the coating behavior at various process parameters. The multilayer coatings are then deposited by selecting a combination of metal-ceramic or ceramic/ceramic coating on the basis of highest H^3/E^2 value obtained from the mechanical analysis.

In order to estimate the mechanical properties of the coatings, Inconel 718 alloy has been used as a substrate in the present study. The choice of Inconel 718 has been made due to its ability to withstand high temperatures (till 700 °C). The most frequent use of In718 is found in the last stages of low pressure compressors of an aero engine.

The research work deals with the deposition parameters used for the deposition of the coatings along with the discussion of the coating structure. Moreover, a discussion on the mechanical properties and the adhesion of the single and multilayer coatings has been added to this section. This section is followed by a crystallographic analysis of the deposited multilayer coatings. An estimation of the crystal size of the deposited coatings was done by analyzing the obtained diffractograms (phase analysis). Moreover, stress analysis of some of the deposited multilayer coatings has been included in order to explain the behavior of the individual metallic and ceramic components affecting the behavior of the coatings.

The next section includes the erosion testing of the deposited single and multilayer coatings. An analysis on the erosion wear has been conducted on an in house developed erosion test rig. A suitable erodent (SiO_2) with defined testing conditions has been used for the test. In order to understand the erosion behavior, the tests have been supported with gravimetric analysis and crack propagation analysis. Erosion rate analysis and their correlation with the measured mechanical properties have been performed to study the process in further detail.

The last section summarizes the important results which were obtained during the research work. Moreover, some recommendations have been added in this section which could be helpful for the development of erosion resistant coatings.

2. Literature Survey

Product Life Cycle (PLC) and asset management have always been key issues for the power generation companies. The integrity of the components after a particular time decides and controls the life of the machine. It has an influence on the direct and indirect costs of the product. Maintenance and repair of the components also play a vital role in improving the life cycle of a commodity. Gas turbine manufacturers have documented severe problems encountered due to the erosion of gas turbine blades especially during takeoff and landing in dusty environments. As a result of material removal, high maintenance costs are required in order to repair and many blades have to be replaced in severe cases [9].

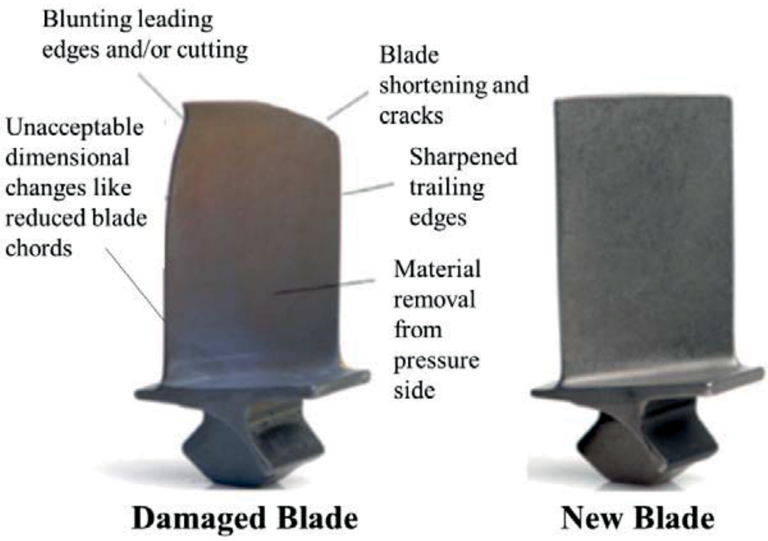

Figure 2.1: A comparison of eroded compressor blade and new blade [10]

Similar to other component degradation processes (fatigue, corrosion, oxidation), Solid Particle Erosion (SPE) has also been identified as one of the major problems which is responsible for the reduction of the life of a component. Solid Particle Erosion (SPE) is a wear process where particles strike against surfaces and promote material loss. Different models have been proposed which estimate the stresses of a moving particle imposing on a target surface [11, 12]. During the impact, the target can be locally scratched, extruded, melted and cracked in different ways. The imposed surface damage will vary with the target material, erodent particle, impact angle, erosion time, particle velocity, temperature, atmosphere and other factors. Solid particle erosion is usually defined in terms of weight loss per unit charge [13]. A comparison between new and tested blade can be observed in Fig. 2.1. Shortening of blade, sharpening of trailing edges, loss of material from pressure side and blunting of the leading edges were reported as some of the effects of the erosion on blades in sandy environments [10].

The main idea of erosion analysis is to understand the erosion mechanisms in general and to characterize the erosion resistance of materials in particular for a selected application (e.g. fluidized beds, nozzle flows, pneumatic flows in pipes etc.). An understanding on the effect of abrasive charge is not only meant to understand the different stages of erosion process but is also helpful in modeling and extrapolating laboratory date more precisely to field conditions [13].

2.1. Deterioration of turbomachinery performance due to erosion of gas turbine components

Erosion of low compressor gas turbine blades has been a serious problem for the manufacturers and users of industrial and aeronautical gas turbines. Particle erosion in compressors lead to the reduction in blade chord, changes in the shape of leading and trailing edge and an increase in surface roughness of the blade surface too [14]. Bons et al. reported an average roughness increase of 4-8 times greater due to erosion in comparison to after production roughness [15]. A lot of research has been conducted to observe the aerodynamic performance of the fan and blades after erosion which was determined in terms of blade geometry, axial flow velocity, flow angles, upstream pressure, temperature and Reynolds Number [3]. Ghenaiet *et. al* [16] reported a degradation of engine performance due to the blunting of blade leading edges, reduction of chord and increase tip clearance and surface roughness. Simulations on the reduction of static pressure after erosion with a mass flow of 0.69 kg/s are depicted in Fig. 2.2a. It is very clear from the illustration that high pressure drop occurs at the pressure and the suction side. Adiabatic efficiency which determines the efficiency of the engine after heat gain or loss which is important in order to acquire the actual work (Fig. 2.2b) showed a decrease of in 10 % after the ingestion of sand for 9 hours. Another important aspect is the pressure rise coefficient which determines the pressure drop passing through the turbomachine and is responsible for the engine efficiency.

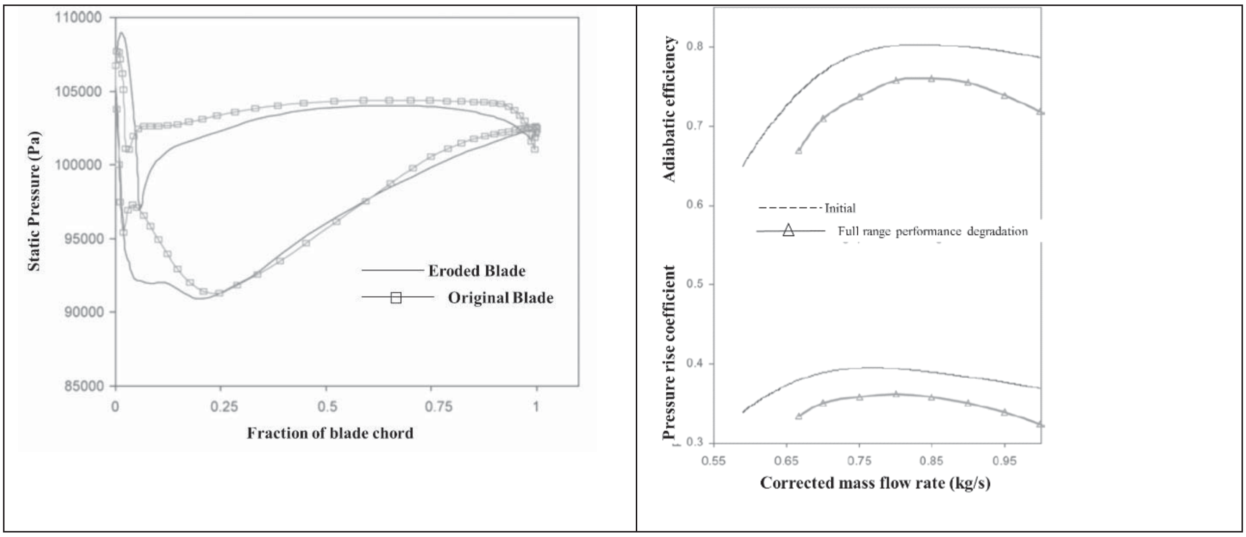

Figure 2.2 :(a) Static pressure observed around blade near tip (b) corrected mass flow rate with reference to change in pressure rise coefficient and adiabatic efficiency [16]

This ingestion of sand in the engine does not only lead to loss in power of the engine but also reduced Mean Time Between Overhauls (MTBO) which leads to increase in logistic support and the associated costs [4]. Maintenance costs of a three-stage blisk compressor were estimated to be about $ 200.000 per year whereas $1.000.000 for large compressors [17]. Another aspect of the erosion of compressor components is inefficiency of the fuel system which can lead to high costs for the organizations. A comprehensive study of the increased fuel consumption due to the erosion in turbine has been made by Uihlein et. al [17] where he reported an increase of 0.02 % of specific fuel consumption for an engine which does not land in dusty environments. The eroded components of such engines can be changed after 3000 cycles of flying. Alternatively, engines which are used in high aggressive dusty environments show an increase of 0.05% specific fuel consumption and the life time of the components were reported not to be more than 2000 cycles.

2.2. Solid Particle Erosion

Erosion because of solid particle impact is a complex process combining numerous wear processes instantly. A particle with a high velocity strikes the surface of the material imparting its kinetic energy into it. A consequence of this transfer of energy is the deformation of surface or removal of material. A number of factors have been discussed in literature describing their influence on the erosion process. Some of them can be found in Tab.2-1:

Material Properties	Particle Properties	Air/Atmospheric Properties
Fracture Toughness [18]	Shape [19, 20]	Incidence Angle [21, 22]
Hardness [23]	Size [24-26]	Particle Velocity [27, 28]
Material structure [29]	Hardness [30]	Particle Rotation[31]
Intinisic Stresses [32]		Particle Flux [33]
Microstructure [29]		Temperature [21, 34]
		Humidity[35]

Table 2.1: Factors influencing the erosion phenomenon

On the other hand a number of models have been discussed in literature to study the erosion behavior of systems. One of the first models developed for ductile materials was proposed by Finnie [28]. He studied the behavior of ductile materials by varying the incidence angles and velocity of the erodent. Finally he formulated a numerical model which predicted the erosion behavior of ductile materials. The proposed model also predicted that when particles attack a surface at shallow angles, craters having a length/depth ratio of 10:1 were observed depicting a cutting mechanism clearly. Nelson and Gilchrist [36] studied a number of ductile materials and found that deformation takes place when an alloy is attacked at normal angles.

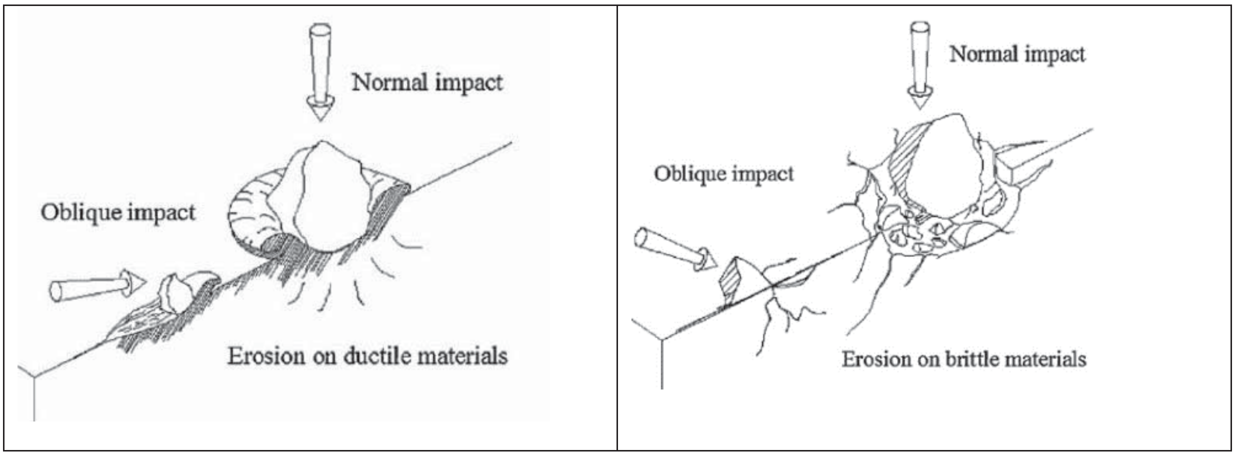

Figure 2.3: Erosion mechanism in (a) ductile (b) brittle material [37]

A schematic model of the erosion mechanism in a ductile material is depicted in Fig.2.3 [37]. They made an FEM analysis in order to understand the erosion behavior of Ti6Al4V alloy and found that material removal due to plastic deformation is one of the major wear processes at lower impingement angles for ductile materials. With increase in impingement angle, low material removal is observed due to an increase in plastic deformation. Hence, maximum depth of penetration occurs at oblique angles. Erosion in brittle material is generally defined by the Hertzian crack theory. According to Hertzian theory, the particle kinetic energy of the erodent is converted into the elastic deformation energy. When the deformation energy exceeds the elastic limit of the material, a plastic deformation is ought to be observed within the material [38]. Similar to ductile materials, a FEM model for the erosion of brittle materials was also devised by Wand and Chang (Fig. 2.3b) [37]. They found that formation of subsurface cracks is the major reason for the failure of brittle material. The normal component of the impinging velocity is responsible for the subsurface cracking the target. At oblique angles, a maximum value was observed for the normal component of the alloy. Moreover, high crack coalescence of the subsurface cracks is also observed at oblique angles. The behavior of penetration depth and the development of residual stresses in the subsurface are similar to that of ductile materials.

2.3. Physical Vapor Deposition

Physical Vapor Deposition (PVD) has been an effective method in order to deposit thin films which protect the surfaces from external effects.

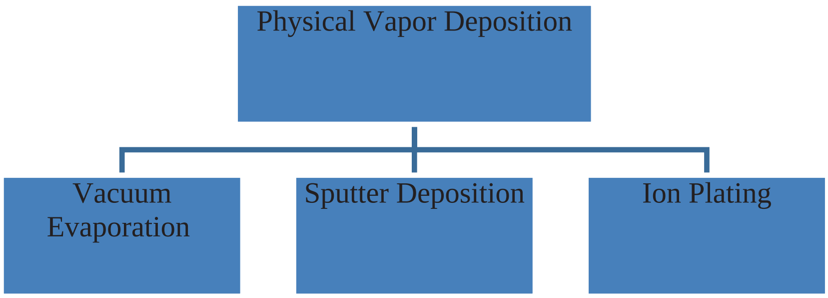

Figure 2.4: Classification of PVD Methods

PVD is a vacuum process where material is transported from an evaporator or a magnetron source in the form of vapors and then condensed on a suitable substrate. Vacuum evaporation refers to the thermal vaporization or sublimation of the source into vapor phase. Typical vacuum pressures of 10^{-3} to 10^{-6} Torr are used during vacuum evaporation processes depending on the contamination within the vacuum chamber. One of the main advantages of vacuum arc processes is the use of evaporator in solid as well as in liquid or gaseous form. Moreover, high purity in the deposited coating can be observed through this process. This method also offers an easy control and monitoring of deposition process. Good adhesion, high evaporation rates (approx.. 10^{-3} g/cm^2s) and constant coating thickness are identified as advantages of the vacuum evaporation process [39].

Another PVD method often used is the magnetron sputtering process. In this process, Argon is used as a process gas and act as a medium for the transport of ions towards substrate. In comparison to vacuum evaporation, the coating material is not heated to transform into gas but are knocked out from the coating target in form of ions. Magnetron sputtering offers better adhesion due to highly energetic ions along with low sputtering rates [39]. Detailed information regarding the magnetron sputtering can be found in Section 2.3.1.

A third sub classified form of PVD method is the ion plating method. With the improvement of electro-magnetic field within the coating chamber (through the addition of strong magnets), high energy ions can be collected on the substrate. An increase in sputtering rate with a similar ion energy was reported for ion implanting as compared to magnetron sputtering. Moreover, the high adhesion and low deposition temperatures were also found to be among some advantages of ion plating process [39].

2.3.1. Magnetron Sputtering

In a basic magnetron sputtering process plasma is created in which the positively charged ions (Argon ions in most cases) are used to eject the electrons form the negatively charged targets. In order to eject the atoms from the target, the ions should have enough energy to dislodge the atoms from the target. The ejected atoms would find their way and condense on the substrate which is present in the proximity of the magnetrons. Secondary electrons are also generated in this process which play their role in maintaining the plasma as can be observed in Fig. 2.5a. Magnetrons which are located behind the Metal or compound target, are series of magnets which are responsible for the concentration of electrons in the vicinity of the target. This concentration of electrons will lead to a higher probability of electron-atom collision resulting in increased ion bombardment of the target, higher sputtering rates, higher deposition rates etc. [40].

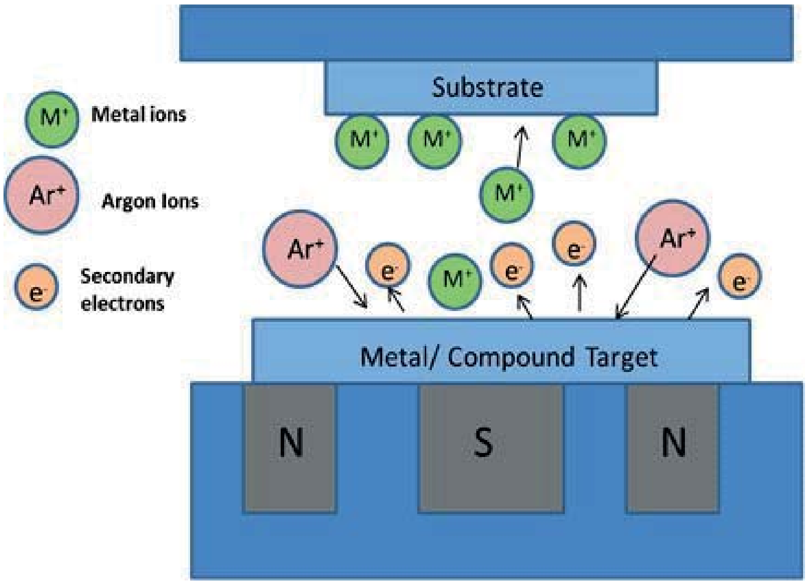

Figure 2.5: (a) Schematic of a magnetron sputtering process (b) Plasma generation in a conventional circular magnetron

A configuration of the conventional or balanced magnetron sputtering is depicted in Fig. 2.6a. In this case almost all of the field lines are trapped between the poles. In such a configuration the plasma discharge is concentrated in the target region due to high efficiency of trap and therefore the distance between target and substrate plays an important role [41]. Low coating deposition rates, low ion current densities, low energy of atoms during deposition are some of the properties defined for balanced magnetron sputtered coatings in literature [42].

In case of unbalanced magnetron sputtering (Fig. 2.6b), the magnetic field is directed towards the substrate by using high volume magnets leading to intensification of magnetic field at outer poles. In this case the plasma is not concentrated to the targets and allows a flow towards the substrate [40]. An important parameter is the ion-to-atom ratio which defines the structure development and properties of the coating. In case of unbalanced magnetron sputtering, the ion-to-atom ratio remains fixed at a constant target to substrate distance [41].