Chapter 1
Introduction

1.1 Introduction:

AISI 4340 steel (En-24 steel), a member of the family of low- alloy steels, constitutes a very important engineering material employed in the manufacture of different structural components which encompass automotive crankshafts and rear axle shafts, aircraft crankshafts, connecting rods, propeller hubs, gears, drive shafts, landing gear parts and heavy duty parts of rock drills, among others. It is a heat treatable, medium-carbon type of low- alloy steel having superior mechanical properties owing to presence of nickel, chromium and molybdenum as the principle alloying elements. After an appropriate surface modification treatment, this steel is recommended for applications involving severe conditions of wear, corrosion and cyclic loading.

Surface modification or surface engineering is that area of engineering which deals with 'engineering of the surface' of a material or component to confer the surface properties, that are different from the bulk properties of the base material. The purpose of surface engineering may be thus to reduce wear, minimize corrosion, increase fatigue resistance, act as a diffusion barrier, provide thermal insulation or simply improve the aesthetic appearance of the surface using different surface modification or coating techniques.

Failure due to fatigue is a result of initiation of a crack, by and large at the surface of the component, and its subsequent propagation as a consequence of cyclic loading of the component. It is found that a component fails due to fatigue under cyclic loading condition at stress levels much lesser than even its yield strength. About 70% of total failures of cyclically loaded components are due to fatigue. Thorough understanding of the fatigue behaviour is therefore essential for components subjected to constant variable amplitude loading.

It is realized that improvement in fatigue resistance of components can be derived primarily by decreasing the surface cyclic tensile stress or by increasing the surface yield stress, thereby increasing the resistance to fatigue crack nucleation. In practice this can be ensured by changing the characteristics of the surface region of a component by changing the composition and/or its surface microstructure using chemical conversion coatings and/or thermo-mechanical processes so as to induce residual compressive stresses at the surface leading to enhancement in the fatigue life.

Some of the surface modification or coating processes developed industrially to improve the wear, corrosion and fatigue resistance of a steel include processes like hard chrome plating, thermal spray coating, heat treatments like carburizing, nitriding, carbonitriding and induction hardening; methods involving non-uniform plastic deformation like shot peening, or methods such as ion implantation and chemical or physical vapor deposition, etc. However, it is realized that the improvement in surface properties of steel by means of coatings (so as to increase its performance against wear and corrosion) often significantly deteriorates its fatigue behaviour. It is found that quite a few of these surface modification techniques lead to reduction in fatigue strength, but for the exception of techniques like nitriding (based on gas, salt bath or plasma energy) that are known to enhance the fatigue strength.

Effect of chrome plating on fatigue life of steel substrates has been a subject of study for dynamical applications since long. However, the fact remains that the fatigue life of steel subjected to hard chrome plating has been found to depend on factors like residual stresses in the coating, micro-crack density and the nature of the coating/substrate interface, etc. In most of the cases, a negative effect of hard chrome plating is observed on the fatigue life of steel substrate.

Likewise, effect of thermal spray coatings on fatigue life has been extensively studied over the years for plain carbon (medium carbon) steels as well as low-alloy steels. The fatigue life is found to decrease in most of the cases while in few cases no effect on base material's fatigue life is observed. In certain cases fatigue life is found to increase also. Thus the present understanding of fatigue behavior of steels subjected to thermal spray coatings is inconclusive and so there is a scope for further investigation in this direction.`

One of the methods used to enhance the fatigue life of the rotating components that are subjected to cyclic loading, is nitriding. Nitriding is a group of surface-hardening processes based on the thermo-chemical principle involving the introduction of nitrogen into the surface of the steel by processes like gas nitriding, liquid / salt bath nitriding and plasma / ion nitriding. Nitriding produces a strong and shallow case with high compressive residual stresses on the surface of the steel so as to improve its fatigue life. Rotating bending fatigue tests on nitrided steel samples show higher fatigue limit than their un-nitrided counter parts. However, the conventional nitriding processes based on gas or salt bath have certain limitations being messy and less environment-friendly and hence plasma or ion nitriding process is preferred. Plasma nitriding is an advanced surface modification technology which has experienced substantial industrial development over the past 30 years. It is a process of surface hardening using glow discharge technology to introduce nascent (elemental) nitrogen into the surface of a metal part for subsequent diffusion into the material. Under high- vacuum conditions, high-voltage electrical energy is used to form plasma, through which nitrogen ions are accelerated to impinge on the work piece. The ion bombardment heats the work piece, cleans the surface, and provides active nitrogen. Nitrogen diffusion modifies surface and near surface microstructure producing hard layer.

The layer on the nitrided steel consists of two parts namely, compound layer and diffusion layer. The outer thinner layer consists of mainly γ-Fe_4N and/or ε-$Fe_{2,3}N$ inter-metallic phases. It is commonly called as 'compound layer' or 'white layer' because of its white color after Nital etch on the microscopy and has a thickness of some micrometers. Thickness and phase content of compound layer depend on the treatment parameters such as gas composition, time and temperature of nitriding, etc. The layer, beneath the compound layer, is known as 'diffusion layer' which consists of mainly interstitial atoms in solid solution and fine coherent nitride precipitates when the solubility limit is reached. The diffusion layer is relatively thick and strong. It constitutes the subsurface of a steel component with a gradual reduction in the hardness and nitrogen concentration towards the core, resulting in a diffused case - core interface.

1.2 Scope and objective of work:

In this work an attempt has been made to modify the surface characteristics of the hardened & tempered AISI 4340 steel specimens subjected to various surface modification treatments like hard chrome plating, thermal spraying and plasma nitriding and to examine their effect on fatigue behaviour of this steel. The methodology of smooth bar rotating bending fatigue testing, using a R. R. Moore type rotating bending fatigue testing machine is adopted for evaluating the fatigue behaviour after respective surface treatments. The surface treated specimens were characterized for coating thickness, surface hardness and/or hardness profile, phase identification using XRD, optical and SEM fractography, microstructure and the effect of coating thickness on fatigue life using finite element analysis (FEA) approach. Basquin type power law relationship for alternating stress amplitude versus cycles to failure was derived in each case. Based on these plots, the surface treatment modification factors have been arrived at.

The review of literature indicates that researchers have established strong correlations between the number of non-material factors (such as the numerical value of the applied mean stress, magnitude of stress concentration, operating environmental temperature, size of the component, fabrication state, surface finish of component, etc) and the fatigue life of a material under investigation. However, the effect of material related factors such as the 'fatigue strength modification factor' and 'cycle modification factor' with respect to the surface modification treatments used have not been fully studied. Since, the fatigue strength modification and cycle modification factors for these treatments are not available in open literature, machine designers are routinely forced to take recourse to large factors of safety in their design calculations resulting in highly non-optimal, costly, cumbersome designs. In view of this, in the present research work it is contemplated to examine the effect of these factors on fatigue behaviour of AISI 4340 steel subjected to surface modification treatments viz. hard chrome plating, thermal spraying with alumina, and plasma nitriding.

It also appears from the literature that for plasma nitriding process the effect of thickness of the compound layer (popularly known as white layer) on fatigue life of steel has not been fully understood. In view of this, during present investigation an attempt has also been made to examine the effect of variation in thickness of compound layer on fatigue strength of AISI 4340 steel.

1.3 Important research findings:

The results of this research work have shown that for the plasma nitrided categories with compound layer < 10 μm and with absence of compound layer, the Fatigue Stress Modification Factors (FSMF), $(\theta_{coat})_i$ are greater than one whereas for plasma nitrided category with compound layer > 10 μm the FSMF value is less than one. The FSMF value is less than unity for chrome plated and thermal sprayed specimens as well. Improvement in fatigue life is noticed when the Fatigue Stress Modification Factors are greater than one.

This investigation has revealed that the categories, which increase fatigue strength are plasma nitrided specimens with compound layer of < 10 μm and plasma nitrided without any compound layer. Whereas, the categories, which decrease fatigue strength are hard chrome plated specimens; thermal sprayed using alumina powders, and the plasma nitrided category of compound layer with thickness > 10 μm. For plasma nitriding treatment the thickness of the compound layer is found to govern the probability of crack nucleation and the nature of the surface residual stresses leading to fatigue.

Thus an important finding of this work is that the presence of compound layer is not always detrimental to fatigue life. In other words, in contrast to the commonly held notion that the presence of compound layer (in any thickness) will always degrade the fatigue life, the present study shows that this is not completely true. The results obtained clearly show that the presence of compound layer up to 10 μm thickness enhances the fatigue strength and fatigue life of the material and the drop in fatigue strength starts only when the compound layer thickness is greater than 10 μm.