Effect of Plasma Nitriding Treatment on Fatigue Life of En-24 steel

U. N. Puntambekar[1^], G. S. Grewal[2], P. B. Joshi[3] and P. Sampathkumaran[4]

Sr. Manager, Technology center, Electrical Research & Development Association, Vadodara, India[1]

Dy. Director, Materials Technology Divison, Electrical Research & Development Association, Vadodara, India[2]

Faculty of Engineering & Technology, M. S. University of Baroda, Vadodara, India[3]

Central Power Research Institute, Bangalore, India[4]

Abstract: In this investigation plasma nitriding has been carried-out to enhance surface related properties of steel components. The hardened case in these components comprise of a compound (white) layer on top followed by a diffusion zone underneath it. The increase in hardness and strength at the surface, yield improvement in fatigue life. However, increase in thickness of the compound layer beyond a certain critical reduces the fatigue life of the base material. Hence, it is desirable to have close control on the process to limit the formation of excessively thick compound layer. The data related to increased fatigue life of various low alloy steels is available in the published literature, but the effect of thickness of compound layer on fatigue life could not be cited in literature. Hence, the present work focuses on this issue.

This paper discusses the effect of plasma nitriding and the thickness of compound layer in particular, for the En-24 steel. The experiments were carried-out on steel rod samples which were plasma nitrided with formation of varying amount of thickness of compound white layer and maintaining diffusion layer depth the same. The characterization of samples was done in respect of chemical composition, microstructure & micro-hardness. The rotating bending fatigue tests on plasma nitrided samples were conducted at various stress levels to plot S-N curves. Based on the fatigue test results, modification factors for stress & life-cycles were established. The data indicate that the fatigue life of samples increases up to a certain thickness of compound layer and then decreases.

Keywords: Fatigue, plasma nitriding, compound layer, low-alloy steel

I. INTRODUCTION

The plasma nitriding is one of the thermo-chemical processes used to harden the surface of steel. In this process, nitrogen diffuses from the surface, similar to other nitriding processes, and forms various nitrides. The type & concentration of nitrides formed depends upon the gas composition, temperature & duration of nitriding. There are two important layers formed on the surface i.e. a compound layer at the surface and a diffusion zone beneath it, extending towards the core. The composition, hardness, strength and residual stress level of the region from surface to core vary continuously & widely. There is a vast difference in the levels of properties of these local regions. One of the key advantages of the plasma nitriding process is the attainment of uniformity of the surface properties and possible control over it through the process parameters. Similar to other nitriding processes, plasma nitriding also enhances the surface related properties such as wear & erosion resistance as well as fretting & plain fatigue strength ([1], [2]).

It is known that the fatigue cracks are by and large initiated at the surface and the fatigue strength of component depends on the surface quality. In general, the fatigue strength depends upon the strength level of surface layer. There are three ways in which the surface treatment influences fatigue strength; firstly, by affecting the intrinsic fatigue strength of material at the surface, secondly by introducing or removing residual stresses in the surface layers and

thirdly, by introducing or removing irregularities in the surface which act as stress raisers [3]. Plasma nitriding enhances fatigue strength by first two mechanisms stated above. Apart from this, extent of increase in fatigue strength also depends upon the factors like, thickness of the case, ratio of case to core area, residual stress levels at case, etc. Substantial data is available on the fatigue strength of plasma nitrided steels. Likewise, relationships have also been established between the case properties and fatigue strength [10].

The effect of nitriding on fatigue life has been studied for AISI 1045 [4], B-Mn steel [5], tool steel ([6],[8],[11]), constructional steel ([7],[14]), Cr-Ni-Mo steel ([9],[13]), AISI 4340 steel [16], AISI 4140 steel ([12],[19],[20],[23]), En-40 B steel ([11],[22]), Cr-Mo steel [17], Cr-Mo-V steel [10], AISI 304 steel [18], & SA 645 steel [15]. The study indicate an improvement in fatigue life in most of the steels ([4], [5], [7]-[17], [20]-[23]), whereas an adverse effect has been observed in tool steel [6] & AISI 304 [8]. It has been reported that the plasma nitriding improves the fatigue strength of AISI 4140 steel and increases the fatigue limit depending on the surface hardness and the case depth [12]. Studies on the effect of plasma nitriding on repair process of fatigue damaged AISI 4140 steel show that the process applied to untreated specimens improves the fatigue life of the specimens that were plasma nitrided. However, for the nitrided specimens, a significant improvement in the fatigue life has not been observed because of the compound layer on the surface prevents the diffusion to occur during the second nitriding [19]. The improvement up to 90% in fatigue strength of base material has been achieved through plasma nitriding for AISI 4340 steel [16].

However, it appears that the effect of variation in thickness of the compound layer (with same diffusion layer thickness) has not been reported in the literature. In view of the above, a study has been undertaken to determine the effect of varying thickness of compound layer on fatigue strength of En-24 steel. The steel selected is the most commonly used material for the shaft applications. This paper describes the details of this study.

The investigation was conducted based on statistical design of experiments. The effect of the various treatments has been systematically studied using various statistical inferential techniques. Basquin type power law relationship for alternating stress amplitude versus cycles to failure has been derived. Based on these plots, the surface treatment modification factors have been arrived at. Further, the results obtained are correlated with the underlying physical processes associated with the various treatments studied.

II.   EXPERIMENTAL & ANALYTICAL METHODOLOGY

A.   Experimental

En-24 grade low-alloy steel, which is a most commonly used shafting material, has been selected for this study. A coil of hot-rolled wire-rod of 20 mm diameter was obtained from steel plant. Subsequently wire drawing was done to obtain scale and decarburization free rods of 18.7 mm diameter. The rod material had an average austenitic grain size No. 6 (as per ASTM E – 115) and controlled non-metallic inclusions index equal to 1.5 as per IS: 4163 – 2004. The composition analysed is shown in Table 1. Figure 1 gives the schematic of the test sample used for fatigue testing, wherein the gauge diameter of 12 mm contains a machined, semi-circular notch of depth 1.5 mm and root radius of 1 mm. This translates into a stress concentration factor of 2, as computed using analytical elastic stress analysis theory. The normalized wire-rods were given hardening & tempering heat-treatment by preheating at 500˚C,austenitising at 855˚C, quenching in oil & finally tempering at 520˚C to obtain hardness of 32±2 HRC ($\cong$ 320 HV). The mechanical properties measured in respect of hardened & tempered wire rods are shown in Table 2.

Table 1 Chemical composition of En 24 steel used as starting material

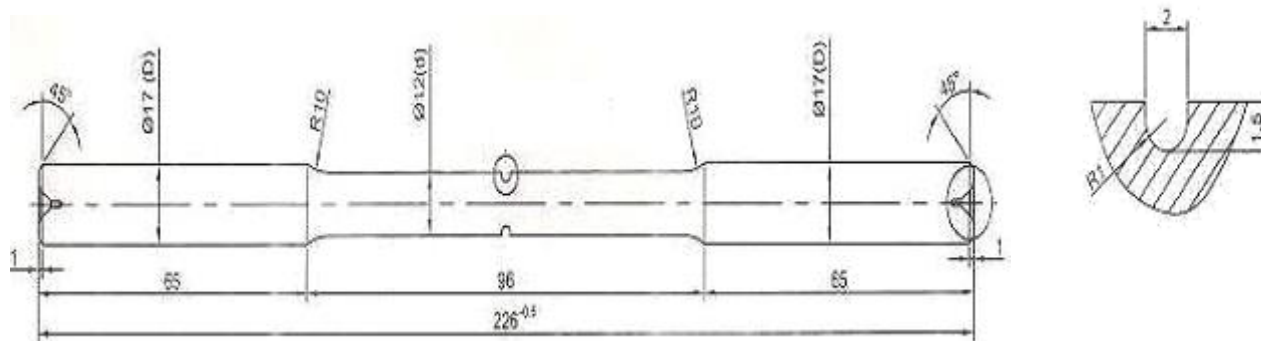| Element	Composition, wt %
Carbon	0.396
Silicon	0.293
Manganese	0.629
Phosphorous	0.013
Sulphur	0.018
Nickel	1.425
Chromium	0.996
Molybdenum	0.205

Figure 1: Schematic of the fatigue test sample

Table 2 Mechanical properties of heat treated En 24 steel wire rod samples

Parameter	Values
Yield Strength σ_y, (MPa)	1073
Ultimate Tensile strength σ_u, (MPa)	1142
% Elongation, δ	13
% reduction in area, ΔA	44
Hardness, R_c	32±2

The machined fatigue test samples were subjected to plasma nitriding to obtain three different thicknesses (categories) of compound (white) layer i.e. without compound layer (category-1), with compound layer thickness of up to 10 microns (category-2) and thickness of > 10 microns (category-3). For all these categories of samples, the nitrided layer thickness was around 400 microns. The surface hardness of the samples after nitriding varied depending on the thickness of compound layer. The mIcrohardness profiles were measured and plotted for the nitrided samples. The surface roughness (R_a, µm) of the samples subjected to fatigue test was around 0.68 for base material (control) and 0.49 for plasma- nitrided samples.

The rotating bending fatigue tests were conducted, using a R. R. Moore type rotating bending fatigue testing machine. The samples without surface treatment (Control category), and surface-treated categories (3 nos. each) were evaluated for fatigue life. Six stress levels with four replications were selected for fatigue evaluation.

B.   Modeling of Fatigue Data

The data generated in the fatigue testing program was subjected to statistical analysis, and the extracted mean field parameters were modeled using the Basquin relationship:

$$\sigma_a = \alpha\left(N_f\right)^{\beta} \quad ....(1)$$

Where:

σ_a = Alternating stress (stress amplitude)

N_f = Number of cycles to failure

α , β = Basquin pre-exponent and fatigue life exponent, respectively

Once the Basquin type relationships given by Eq. 1 have been developed for the base material (control) and the three treatment categories, the following additional parameters are
extracted, for deriving the "surface modification" factors on the fatigue life/strength.

B1.   Fatigue Stress Modification Factor, $(\theta_{coat})_i$

$$(\theta_{coat})_i = \frac{(\sigma_a)_i}{(\sigma_a)_b} = \frac{\alpha_i(N_f)^{\beta_i}}{\alpha_b(N_f)^{\beta_b}} = \left[\frac{\alpha_i}{\alpha_b}\right]\left[N_f^{(\beta_i-\beta_b)}\right] = \theta_{PEi}N_f^{\theta_{Ei}} \quad .... (2)$$

Where:
i   = i^{th} treatment category
b   =   Base material (control category)
α_i , α_b =   Basquin pre-exponent for i^{th} treatment and control categories, respectively
β_i, β_b =   Basquin exponent for i^{th} treatment and control categories, respectively
θ_{PEi}, θ_{Ei} =   Life reduction pre-exponent and exponent, respectively for treatment i.

It is to be noted that the inverse Basquin exponents are derived by switching the role of dependant (N_f) and independent variables.

B2.   Fatigue Cycle Modification Factor, Ψ_i

$$\frac{\left(N_f\right)_i}{\left(N_f\right)_b} = \Psi_i = \frac{\xi_i(\sigma_a)^{n_i}}{\xi_b(\sigma_a)^{n_b}} = \left[\frac{\xi_i}{\xi_b}\right]\left[\sigma_a^{(n_i-n_b)}\right] = \Psi_{PEi}\sigma_a^{\Psi_{Ei}} \quad ...(3)$$

Where:
i   = i^{th} treatment category
b   =   Control (base material) category
ξ_b, ξ_I =   Inverse Basquin pre-exponent for control and i^{th} categories, respectively
η_b, η_I =   Inverse Basquin Exponents for control and i^{th} categories respectively
Ψ_{PEi}, Ψ_{Ei} =   Cycle reduction pre-exponent and exponent, respectively for i^{th} treatment.

In the present work, the effect of surface modification is elucidated by deriving the Fatigue Stress Modification Factor (FSMF), $(\theta_{coat})_i$ given by Eq. (2). The data have been discussed based on the results presented in the following section.

III.   RESULTS & DISCUSSION

The chemical composition of the material used matches well with the standard specification, and does not contain any impurities which can otherwise lead to lower fatigue life. The Micro hardness profile (Figure 2) indicates that total case depth ($400\,\mu m$, considering 400 HV as threshold for a core hardness of 320HV) is almost similar for all the three categories. The sharp decrease of hardness in the samples with higher compound layer thickness ($>10\,\mu m$) as against smooth curves for other two categories, is as expected.
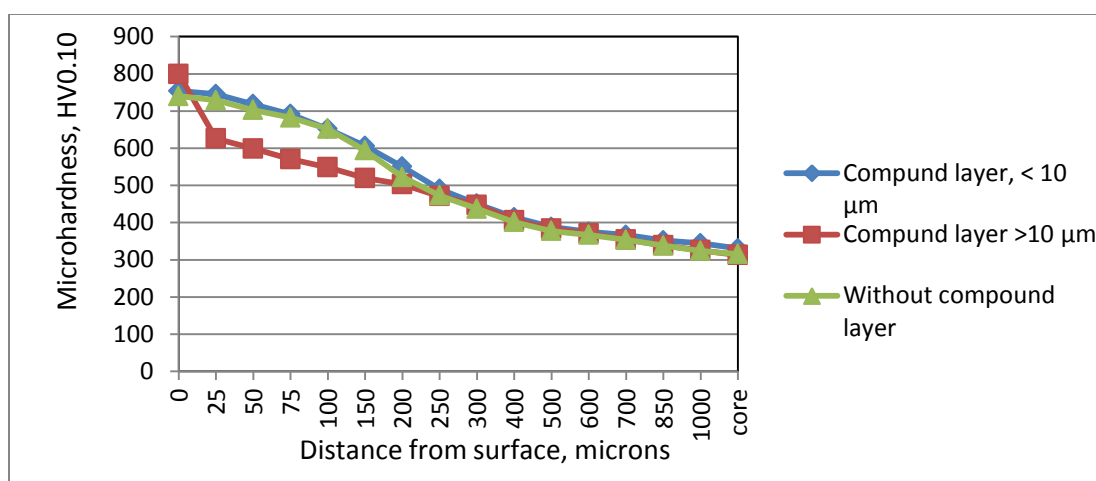

Figure 2: Microhardness profile for nitrided samples for three different categories

The results obtained in terms of the number of cycles to failure at any given alternating stress level for the untreated samples (control) as well as for the three categories of plasma nitrided (with compound layer $> 10\,\mu m$, compound layer $< 10\,\mu m$, & free from compound layer) samples are shown in Basquin plots given in Fig.3 (a) to (d). In these plots, the predictions of the derived Basquin relationships as per Eq. (1) are superimposed on the experiment data. Based on the results obtained, the Basquin pre-exponents and post-exponents for control and various treatment levels are compiled in Table 3, below

Table 3: As derived Basquin Exponents & Pre-exponents for untreated and nitrided En 24 steel samples
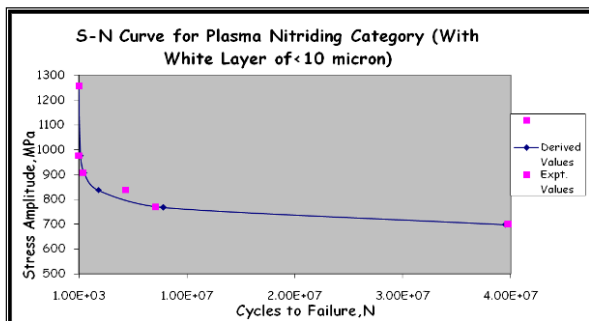
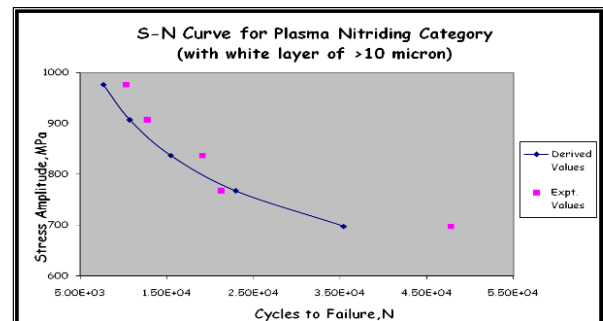| Category	Basquin Pre-exponent (α_i)	Basquin Post-exponent (β_i)
Untreated (Control)	3.31E+03	-0.11
Plasma nitrided ((category-1)	1.958E+03	-0.059
Plasma nitrided ((category-2)	6.974E+03	-0.22
Plasma nitrided ((category-3)	1.45E+03	-0.027
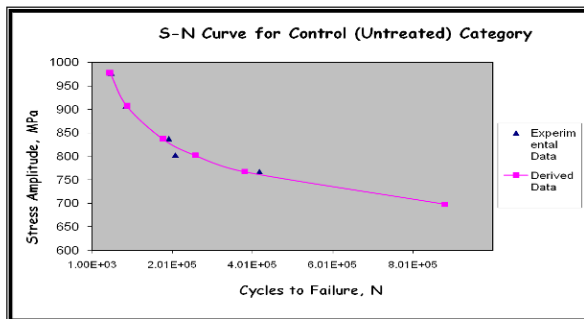
(a)
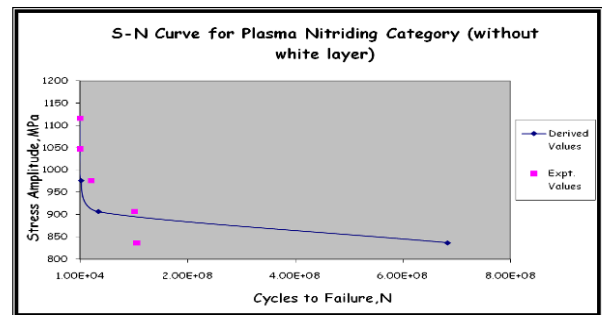
(b)

(c)

(d)

Figure 3: Basquin type plots for alternating stress versus cycles to failure for: (a) control category, (b) plasma nitriding category without compound layer, (c) plasma nitriding category with compound layer of less than 10μm thickness and (d) plasma nitriding category with compound layer of greater than 10μm thickness.

To determine the effect of the nitriding on fatigue life, the Fatigue Stress Modification Factor (FSMF), $(\theta_{coat})_i$ are derived, using Eq. (2), and the Basquin coefficients derived as per Table 1. The superposed Fatigue Stress Modification Factor (FSMF) for the three Plasma Nitrided categories is presented in Fig. 4.
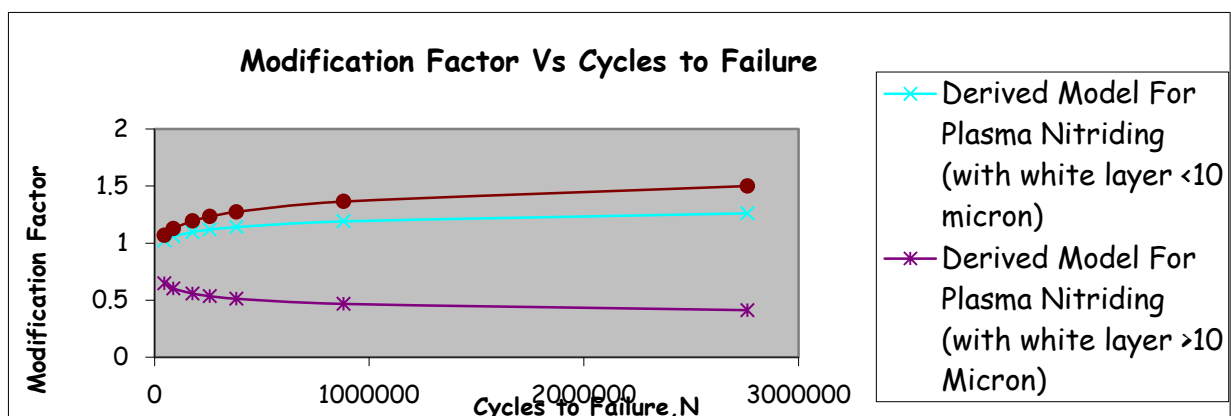

Figure 4: Stress modification factor versus cycles to failure for all categories studied

ISSN: 2319-8753

It is seen from these plots that the severest stress reduction occurs for the plasma nitrided category with compound layer greater than $10\,\mu m$. For this category, the Fatigue Stress Modification Factors (FSMFs), $(\theta_{coat})_i$ are fractional (less than one), and undergo a monotonic decrease with an increase in the number of cycles to failures.

In other words, if one were to plot a superposition of the Basquin plots for this category (with thickness of compound layer greater than 10 microns) with reference to the control - untreated category, the Basquin plots will be translated downwards - parallel to the alternating stress axis - and leftwards - parallel to the "number of cycles to failure" axis.

On the other hand, for the plasma nitrided categories, with compound layer less than $10\,\mu m$ as well as with "absence of compound layer", the Fatigue Stress Modification Factors (FSMFs), $(\theta_{coat})_i$ are greater than one, with the plasma nitrided category without compound layer showing the highest increase in the stress modification factor. The presence of compound layer less than $10\,\mu m$ is seen to degrade the fatigue resistance as compared to the fatigue resistance for the plasma nitrided category without the compound layer. Thus, plasma nitriding (without compound layer as well as plasma nitriding with compound layer lower than $10\,\mu m$) increases fatigue life by delaying the onset of fatigue crack nucleation and also possibly the "fatigue crack growth rate" – at least – through the nitrided layer. The difference in the fatigue strength of compound layer greater than 10 micron and less than 10 micron, respectively, is essentially associated with interaction effects of compound layer thickness with the state of residual stress. It is known that compound layer tends to have principal residual and octahedral normal stresses in the tensile mode. Further, the probability of fatigue crack nucleation is directly proportional to the volume of compound layer. Thus, for larger thickness of compound layer, the probability of crack nucleation will be higher and will decrease as the thickness of the compound layer reduces. At a critical threshold value of the thickness, the probability of crack nucleation in the diffusion zone can easily become larger than in the compound layer. Similarly, below a threshold thickness of compound layer the residual stress can switch to the compressive mode leading to enhanced fatigue strength. However, more work is required to be done to verify these conjectures, by conducting a systematic experimental investigations and analysis of residual stresses in the compound layer as well as quantum chemical calculations using a quantum chemistry package.

Thus, present investigation reveals that the Plasma Nitriding - in the presence of compound layer less than $10\,\mu m$ - does not degrade fatigue life/strength but, in-fact, results in its increase. In other words, in contrast to the commonly held notion that the presence of compound layer (in any thickness) will degrade the fatigue life, the present study shows that this is not completely true. The exact effect of the compound layer on the fatigue life depends on two thickness regimes of the layer. Thus, when the compound layer thickness is greater than $10\,\mu m$, the fatigue life is markedly degraded. On the other hand, for compound layer thicknesses less than $10\,\mu m$, the effect on fatigue life is positive, albeit a little lower than the fatigue life of plasma nitriding coating without any compound layer.

The photo macrographs of the fractured surfaces of typical control, plasma- nitrided (without compound layer) and plasma nitrided (with compound layer) are shown in Fig. 5.
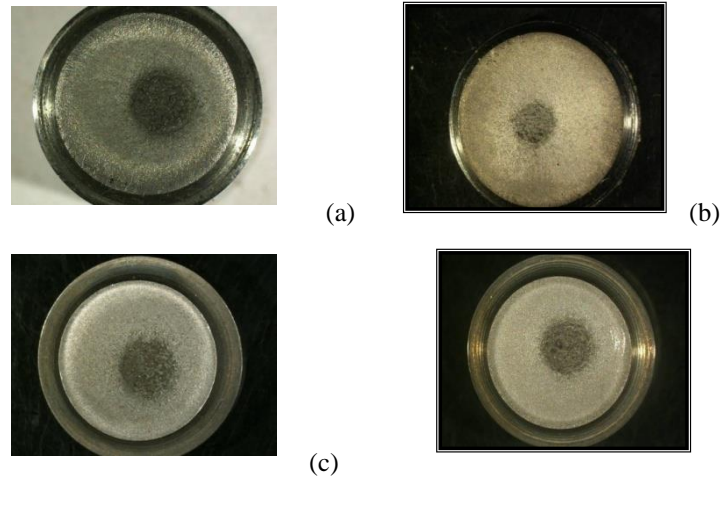
(a) (b) (c) (d)

Figure 5: Macro photographs showing dullish, central, final fracture core surrounded by ring of bright fatigue fracture surface on: (a) a typical control (untreated) sample, (b) plasma nitrided sample without compound layer, (c) plasma nitrided sample with

compound layer of < 10 μm and, (d) with compound layer > 10 μm

It is observed that the central - final fracture core is symmetrical with respect to the axis of the test sample. It is also noticed that the outer circumferential of the sample surface is characterized by the absence of any significant visually apparent texture or asymmetry which can be associated with a site for gross fatigue initiation. A "Fish Eye" type crack initiation ([5],[9],[10],[13]-[16],[21]-[23]) which normally correlates with the presence of non-metallic inclusions ([14]-[16]) has not been observed on the fatigue fractured surface; probably due to close control of the properties of the starting material used. Figures 6(a) to (c) show the photomicrographs of the plasma- nitrided fatigue test samples without compound layer, with compound layer less than 10 μm as well as with compound layer greater than 10 μm. The light micro-photographs show plasma nitrided surface without compound layer, with less than 10 μm thickness, and with greater than 10 μm thickness.
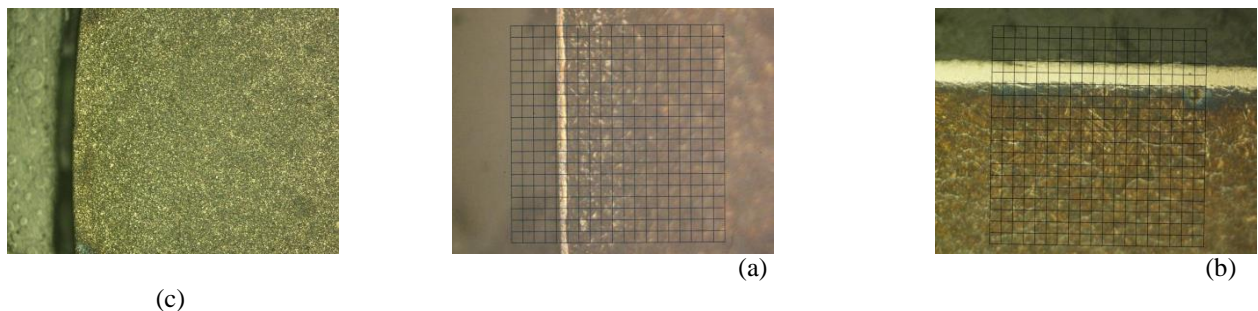

(c) (a) (b)

Fig 6: Microphotographs showing plasma nitrided surface: (a) without compound layer, (b) with less than 10 μm thickness, and (c) with greater than 10 μm thickness. (one division is = 10 μm.).

IV. CONCLUSIONS

Based on the results obtained, the following conclusions drawn are as follows:

1. The experimental fatigue life data agree with Basquin type power- law models with very high values of coefficient of determination, for the control & plasma- nitrided samples (having compound layer greater than $10\ \mu m$, compound layer less than $10\ \mu m$ & free from compound layer).

2. For the plasma- nitrided categories with compound layer less than $10\ \mu m$ and with absence of compound layer, the Fatigue Stress Modification Factors (FSMFs), $(\theta_{coat})_i$ are greater than one. The plasma- nitrided category without any compound layer shows the highest increase in the Fatigue Stress Modification Factor.

3. An important finding of this work is that the presence of compound layer is not always detrimental to fatigue life. The results obtained clearly show that the presence of compound layer up to $10\ \mu m$ thickness enhances the fatigue strength and fatigue life of the material and the degradation starts only when the compound layer thickness is greater than $10\ \mu m$.

ACKNOWLEDGEMENT

REFERENCES

[1] Metals Handbook, 8th Ed. American Society of Metals, Metals Park, Ohio, 1975.
[2] Steel and its heat treatment: Bofors handbook, Karl-Erik Thelning, Butterworth-Heinemann Limited
[3] Fatigue of metals. P. G. Forrest. Oxford 1962, Pergamon Press Ltd.
[4] J. Qian and A. Fatemi, "Cyclic deformation and fatigue behavior of ion-nitrided steel" Int. J. Fatigue Vol. 17, No. 1, pp. 15-24, 1995
[5] P. De la Cruz, M. Ode´n, T. Ericsson, "Influence of plasma nitriding on fatigue strength and fracture of a B-Mn steel", Materials Science and Engineering A242 (1998) 181–194
[6] G.H. Farrahi , H. Ghadbeigi, "An investigation into the effect of various surface treatments on fatigue life of a tool steel" Journal of Materials Processing Technology 174, 318–324, (2006)
[7] Jonas Vilys, Valdas Kvedaras, "Low cycle and high cycle fatigue strength of nitride constructional steels", METAL 2008, 13.- 15.5.2008
[8] Mehmet C_APA, Muza_er TAMER, Turgut G¨ULMEZ, Cengiz Tahir BODUR, "Life Enhancement of Hot-Forging Dies by Plasma-Nitriding", Turk J Engin Environ Sci, 24 (2000) , 111-117
[9] J.D. Costa, J.M. Ferreira, A.L. Ramalho, "Fatigue and fretting fatigue of ion-nitrided 34CrNiMo6 steel", Theoretical and Applied Fracture Mechanics 35 (2001) 69-79
[10] Chang-Min Suh, Byung-Won Hwang, Ri-Ichi Murakami "Characteristics of Fatigue Crack Initiation and Fatigue Strength of Nitrided 1Cr-lMo-0.25V Turbine Rotor Steels", KSME International Journal, Vol, 16No. 8, pp. 1109--1116, 2002
[11] F. Ashrafizadeh, "Influence of plasma and gas nitriding on fatigue resistance of plain   carbon (Ck45) steel" Surface and Coatings Technology 173 –174, 1196–1200, (2003)
[12] A. Celik , S. Karadeniz, "Improvement of the fatigue strength of AISI 4140 steel by an ion nitriding process" Surface and Coatings Technology 72, 169-173, (1995)
[13] M. M. Tosic, I. Terzic, R. Gligorijevic, M. Ognjanovic, "Fatigue improvements of glow-discharge-plasma-nitrided steel rotary specimens" Surface and Coatings Technology, 63 (1994) 73-83
[14] V.F. Terent'ev, M.S. Michugina, A.G. Kolmakov, V. Kvedaras, V. Čiuplys, A. Čiuplys, J. Vilys, "The effect of nitriding on fatigue strength of structural alloys" , ISSN 1392 – 1207 MECHANIKA. Nr.2(64), (2007)
[15] Byung Won Hwang, Chang Min Suh & Ho Kyung Jang, "Effects of Surface Hardening and Residual Stress on the Fatigue Characteristics of Nitrided SACM 645 Steel", Int. J. Mod. Phys. B **17**, 1633 (2003)
[16] Sule Yildiz Sirin, Kahraman Sirin, Erdinc Kaluc, "Effect of the ion nitriding surface hardening process on fatigue behavior of AISI 4340 steel" Material Characterization 5 9, 351-358,(2008)
[17] Mohamed Ali Terres, Habib Sidhom, "Fatigue life evaluation of 42CrMo4 nitrided steel by local approach:Equivalent strain-life-time" Materials and Design 33, 444–450, (2012)
[18] S. Ganesh Sundara Raman, M. Jayaprakash, "Influence of plasma nitriding on plain fatigue and fretting fatigue behavior of AISI 304 austenitic stainless steel" , Surface & Coatings Technology 201, 5906–5911, (2007)
[19] Akgu¨n Alsaran, Irfan Kaymaz, Ayhan C_elik, Fatih Yetim, Mehmet Karakan, A repair process for fatigue damage using plasma nitriding, Surface & Coatings Technology 186 (2004) 333– 338

[20] Aleksander Nakonieczny Solemani, "Fatigue fracture of nitrided and Carbonitrided layers", Journal of Theoretical and Applied mechanics, 44, 3, pp. 713-730, Warsaw 2006

[21] S.M.Y. Soleimani, A.R. Mashreghi, S.S. Ghasemi, M. Moshrefifar, "The effect of plasma nitriding on the fatigue behavior of DIN 1.2210 cold work tool steel", Materials and Design 35 (2012) 87–92

[22] Y. Sun and T. Bell, Plasma surface engineering of low alloy steel, Materials Science and Engineering, A 140 (1991) 419-434

[23] Kenan Genel , Mehmet Demirkol , Mehmet Capa¸ "Effect of ion nitriding on fatigue behaviour of AISI 4140 steel", Materials Science and Engineering A279, 207–216 ,(2000).

BIOGRAPHY

Shri U. N. Puntambekar, Senior Manager, Materials Technology Division, Electrical Research and Development Association, Vadodara

Mr. U. N. Puntambekar graduated in Metallurgical Engineering in 1987 from M. S. University of Baroda, Vadodara. He joined ERDA in 1988 & working, since then, in Materials Technology Div. in the areas of metallurgical testing / analysis, failure investigation, condition monitoring, remaining life assessment etc. He obtained his Master's degree in 2003 in Materials Technology from the M. S. University. He has undertaken several research projects including seven in-house projects, five sponsored projects in the areas of materials technology. He has published / presented about fifteen technical papers in national / international journals.

Dr. G. S. Grewal, Deputy Director, Materials Technology Division, Electrical Research and Development Association, Vadodara

Dr. G. S. Grewal is Deputy Director & Head (Materials Technology Division) at the Electrical Research & Development Association (ERDA), Vadodara. He obtained his B. Tech. (Metallurgical Engineering) from the Banaras Hindu University - Institute of Technology, Varanasi, M. Tech. (Metallurgical Engineering with Specialization in Metal Joining) from the Indian Institute of Technology – Madras and Ph. D. (Chemical Thermodynamics & Transport Phenomenon) from the A. James Clark College of Engineering, University of Maryland, College Park, USA.

His areas of expertise & experience include Thermodynamics, Fracture Mechanics & Mechanics of Materials, Mathematical Modeling of Welding, Chemical, and Metallurgical Processes, Random Variable Statistics, and Risk, Reliability, & Residual Life Assessment of Complex Systems.

Dr. P. B. Joshi, Professor, Department of Materials & Metallurgical Engineering, Faculty of Technology & Engineering, M. S. University of Baroda, Vadodara

Dr. P. B. Joshi graduated in Metallurgy in 1974 from the M. S. University of Baroda, Vadodara. He obtained his Master's degree in Materials Technology in 1976 from IIT-Bombay, Mumbai. He has worked for about five years in industries in the field of powder metallurgy processing. In 1981, he joined M. S. University of Baroda, Vadodara, and since 2006 he is Professor in Metallurgical & Materials Engineering of Faculty of Tech. & Engineering of M. S. University. He obtained his Ph.D. in the field of electrical contact materials in 1992. His areas of interest are powder metallurgy, physical metallurgy, failure analysis & selection of materials. He has guided several students for their project work for graduate as well as post-graduate studies. He has guided two Ph.D. candidates and currently he is guiding one Ph.D. candidate. He has published and presented about 60 research papers in national & international journals. He has one patent to his credit jointly with Dept. of Science & Tech. He has authored a book entitled "Materials for Electrical & Electronics Contacts", published in 2004 by Science Publishers, U.S.A.

Dr. Sampathkumaran P., Joint Director, Materials Technology Division, Central Power Research Institute, Bangalore

Dr. Sampathkumaran P. graduated with B.Sc. (Honors.) degree in Physics from the Bangalore University. He obtained his Master's degree in Physics (Electronics) from the same university and Ph.D. in Physics on Materials Science topic from the Mysore University. He is working in Materials Technology Division of CPRI, Bangalore as a Joint Director in the areas of Material Characterization of metallic, ceramic and polymeric materials, NDT method of measurement like UT, MPI etc., failure analysis of engineering components, remaining life assessment studies on thermal power plant components, development of wear resistant materials. His areas of interest are Tribology, Residual Stress Measurements & Analysis, Structural Integrity of Power Plant Components, Material development for Wear and Friction applications, Abrasion Index of Coal. He has published about 40 research papers in peer reviewed Journals and presented more than 50 technical papers in various National & International Conferences. He has handled various research projects including thirteen in-house projects, three sponsored projects and sixteen consultancy projects. He has guided more than fifty students for B. E and twenty five students for M. Tech programmes. Also, he is a life member of a few Technical Societies.