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# Surface Modification of EN353 Gear Material by Chromium Plating and Plasma Nitriding to Improve Surface Properties, Corrosion and Wear Resistance

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The objective of this work is to find out the optimised parameters to modify the surface properties of EN353 steel by increasing the hardness, and minimizing the loss in wear volume and enhancing the friction resistance in the material. The heat-treated samples of bare substrates were further plated with hard chromium followed by plasma nitriding to modify the surface of the EN353 steel. The nitrided chrome plated specimens were tested in 3.5 wt. % NaCl to test the corrosion properties. Microhardness and tribological properties results indicated that the plasma nitrided chromium plated EN353 steel offers higher hardness and low coefficient of friction when compared to other specimens used in the current study. The microstructure, wear and corrosion studies revealed that the modified layers reduce cracking and spalling on EN353 gear surfaces while electrochemical studies demonstrated an excellent corrosion resistance for the plasma nitrided EN353 steel. The usability of hard chromium plated and plasma nitrided EN353 material in place of hardened one improves the service life of the automotive gear application.

**Keywords:** Hard chromium plating; Plasma nitriding; Heat treatment; Tribological; Microstructure; Electrochemical; Coefficient of friction

# **1. INTRODUCTION**

Plasma nitriding technique, a distinguished surface modification technique, enhances mechanical aspects like corrosion resistance and wear resistance of machine parts [1]. By this technique, various types of steels such as EN353 of low carbon steel modified for automobile

industries such as gudgeon pin, shaft, camshafts and heavy-duty gear because of its good ductility [2], EN 207 is also used for manufacturing the shafts and medium sized gear wheels in the present scenario [3]. Bensely et al. reported [4] that regarding 1500 gear breakdowns were accounted because of tooth wear by abrasive and of fatigue due to tooth-bend, and its associated impact. However the surface nature decides the friction coefficient and upon the availability of less hardness results in higher wears [5]. Hence all the mechanical and tribological components that undergo all types of rolling or sliding contact are subjected to wear and thus wear is an important tribological aspect of failure of the components. The tribological behaviour of the steel can be improved by using two methods: (i) During smelting of integral alloy, the elemental alloys can be added along with the steel and (ii) the other method is surface modification process. Over 30 years of recent advancements in materials surface hardening by plasma nitriding, has grown into essential commercial process [6]. Gear materials require improved properties like corrosion resistance, fatigue strength, wear resistance and surface hardness for which Plasma nitriding or ion nitriding can be used as the most effective techniques [7, 8]. Much attractive properties on coated components in automobile industries have been achieved. Generally, an EN353 material is extremely neither ductile nor brittle in nature because of lower carbon content (soft materials). When the material is subjected for heat treatment process, it leads to carbon increase and thus becomes stronger and harder.

In this present work, the bare substrate of EN353 steel coupons were carried out into hardened, hard chromium coated and was further plasma nitrided to form CrN surface. As of now the Industry prefers to enhance soft material to hard material by heat treatment for gear motion. Thus means, the microstructure was changed, therefore the materials released the stress and transformations occurred in the EN353 material from austenite to martensite reported Navin et al., [19]. After the heat treatment process, the material is cooled in water, air and or oil after the heat treatment process [9]. Low carbon low hardness material enhances the transformation from austenite to martensite when the heat treatment process occurs as reported by Park et al., [10]. Because, the phase structure of the material changed and it gained compressive residual stress. According to Bai et. al., usually the hardness can be increased owing to the formation of martensitic phase reported [11]. Furthermore, fine crystalline structure enhances the localized corrosion resistance in a high manner [12, 13]. Heat treatment process enriches the carbon content on steel and this leads to the metal becoming sturdy [14]. The mechanical behaviour as well as the microstructure of the material can be changed when it is subjected to heat treatment process. Generally, the un-tempered material structure has more hardness and is in brittle in nature. However, tempering is the most suitable process to increase ductility and toughness for enhanced further work on the material without internal stress accumulation.

The purpose of plasma nitriding of chromium EN353 is to offer more hardness to the material surface, increase the resistance to wear, reduce in friction, provide better anti-galling properties, and enhance the corrosion resistance. The nitriding and coating i.e., hybrid treated material shows better resistance to corrosion in the sea atmosphere [15]. The CrN based coating gives better compatibility in PVD coating to provide better resistance to wear and corrosion resistance of EN353 gear material in 3.5 wt. % Sodium Chloride (NaCl) solution [16]. It was reported that the nitriding coated layers with suitable thickness and temperature at 450 °C produced a more hardness in surface, better corrosion and wear resistance with most expanded face centered cubic phase [17].

## 2. MATERIALS AND METHODS

Low carbon low alloy steel EN353 material is considered. The presence of chemical composition of the EN353 is shown in Table. 1. Sivanandham et al., [18]. The as such received bare material of EN353 was hardened by mesh belt furnace at 900 °C for 30 minutes and it was slowly cooled down from carburizing temperature and quenched to transform the austenite. The hard chromium is coated on EN353 bare sample for 50 micron by using electroplating technique. In the present work four samples namely, (i) bare material (EN1), (ii) bare + hardened (EN2), (iii) bare + plasma nitrided (EN3) and (iv) bare + chromium plated + plasma nitrided (EN4) were considered for analysis. All the four EN353 steel specimens were abraded metallographically using silicon carbon (SiC) emery sheets to obtain an even and smooth surface irregularity of  $0.1 \pm 0.02 \mu m$ . The processed EN353 materials were cleaned with running water and then ultrasonically cleaned using acetone bath for removal of the existing dirt and crusts.

Table 1. Elemental chemical composition of the bare EN353 alloy steel (Wt %).

Element	С	Mn	Р	S	Si	Ni	Cr	Мо	Fe
Content (Wt %)	0.19	0.85	0.03	0.03	0.25	0.55	1	0.15	Balance



Figure 1. Detailed schematic diagram of Plasma Nitriding unit.

Plasma nitriding is a technique in which the plasma is generated between the cathode (negatively charged electrode) and the anode (positively charged chamber) at the ground potential. It consists of plasma reactor, vacuum pump, thermocouple, gas inlets, cage, controllers, various sensors etc. The plasma nitriding schematic diagram is presented in Fig. 1 and the operating parameters are listed in Table. 2.

The as such received bare processed samples of EN353 was hardened by MESH BELT FURNACE-SAN-YOUNG-Taiwan at 900 °C for 30 minutes and it was slowly cooled down from carburizing temperature and quenched to transform the austenite. To investigate the interaction characteristics between EN353 low carbon alloy steel and nitrogen during plasma nitriding, a high plasma nitriding surface improvement was carried out using a glow discharge plasma unit, in which vacuum chamber made up of stainless steel was evacuated to 0.01 Pa. Hydrogen (H<sub>2</sub>) and Nitrogen (N<sub>2</sub>) gas were used to produce the plasma and their flow rates were controlled by mass flow meters. The working pressure was 300 Pa. The samples were connected to negative terminal and Plasma nitriding of the samples were carried out at the temperature of 450 °C for 4 hours duration. The temperature was measured by thermocouple. The impact strength of the fabricated specimen was conducted with a speed of 5 mm per minute and 100 mm gauge length.

**Table 2.** Complete operating parameters conditions used for Plasma Nitriding.

Parameters	Pressure	Temperature	Current (A)	Voltage	Duration	Nitrogen	Hydrogen
	(Pa)	(°C)		(V)	(hrs)	$(N_2)$	(H <sub>2</sub> )
Values	300	450	0.76	550	4	80 %	20 %

The phase formation of the nitrided layers were observed using X-ray diffractometer (XRD) (Smart Lab SE X-Ray; Make-Rigaku, Japan) with Cu K $\alpha$  ( $\lambda$ =1.5418 Å) radiation, which was activated approximately at 40 kV and 40 mA. The crystallite size was evaluated using Scherrer's formula from the broadening of full width at half maximum (FWHM) of strongest diffraction peak. Surface morphology has been studied using Field Emission Scanning Electron Microscope (FESEM) (SUPRA55 Carl Zeiss, Germany). The considered samples micrograph images of FESEM and Energydispersive X-ray spectroscopy (EDAX) have been examined. The electrochemical impedance spectroscopy (EIS) experiment was carried out with the NaCl solution of 3.5 % weight and at the room temperature of 25 - 27 °C using an electrochemical workstation (Biologic SP-300, France) system. In this experiment, three flat type electrodes (a saturated calomel electrode (SCE) as reference, working and platinum counter electrode) were used for all measurements. Sample exposed area was 1 cm<sup>2</sup>. However, EIS measurements were taken in the open-circuit potential (OCP) and initially it was monitored for one hour duration and thereafter it was carried out using a 5 mV sinusoidal potential modulation from 100 kHz to 10 MHz. Potentiodynamic polarization was carried out till the pitting corrosion was noticed by stepping up the potential at a scan rate of 0.1667 mV/s, from -500 mV to 500 mV versus open circuit potential (OCP Vs SCE). The tribological behaviour, of the treated samples, has been studied using (DUCOM-542) by pin-on-disc method to evaluate the EN353 treated and untreated specimens at dry ambient conditions with slide speed, normal load, slide distance and relative humidity (RH) as 0.3 m/s, 5 N, 200 m and 61 % respectively using WC counter pin balls. The wear rate and coefficient of friction were calculated for the samples at initial weight, before test and weight after test according to the Eq.1 and 2 reported by Astunkar et al. [19];

$$Q\left(\frac{mm^3}{m}\right) = \frac{v}{s} = k\frac{F_n}{h} \tag{1}$$

where, Q - wear rate, V - cumulative lost volume S, - sliding distance,  $F_N$  - normal load, h - hardness (HV) from Eq. (1), and wear coefficient is given by

$$K = \frac{Q_h}{F_n} \tag{2}$$

## **3. RESULTS AND DISCUSSION**

3.1 XRD analysis



**Figure 2.** X-ray diffraction patterns of (a) bare material (EN1) (b) bare + hardened material (EN2) (c) bare + hardened+ plasma-nitrided material (EN3) and (d) bare + hardened + hard chromium plated + plasma nitrided material (EN4).

Fig 2 depicts the XRD forms of both untreated as well as treated EN353 of the range of  $35-80^{\circ}$ . XRD peaks for the untreated specimen in Fig. 2(a) shows  $\alpha$ -Fe phase with peak reflections in agreement with reported reference (JCPDS Ref No. 06-0696). Fig 2(b) is for plasma nitrided samples of steel EN353. Fig 2(c) is for hardened followed by plasma-nitrided material and Fig 2(d) is for bare + hardened and hard chromium surface treated samples in which peaks in addition of Fe-Cr-C and Fe-Mn-C are seen. JCDPS evaluation was done in several phases against for treated samples and confirmed the existence of iron carbides with martensite phases. Further surface treated the XRD peak

intensity of hardened + hard chromium plated and plasma nitrided (EN4) could increase compared to others, which might be achieved because of martensite phase transformation. At intermediate, better microstructure and hence improved mechanical properties occur, reported by Sivanandham et al. [18]. In Fig. 2(d), at 54.8° there has been a diffraction peak of super saturation that dignifies the solid solution of nitrogen, which could not be suited with any phases including iron, FeN, and CrN in the nitride surface and it is an expanded martensite [20]. A weak peak of CrN is also visible. The CrN was found in the layer of nitrided region due to the chemical interaction of nitrogen with Cr at the nitriding temperature. From the obtained peaks (200), (310), (302), (214), (222), (220), (002), (300) and (521) it shows that the material EN353 (both treated and untreated) used gives the face centered cubic (FCC) crystalline structure.

#### 3.2 Microstructure analysis

The microstructures of the hardened and unhardened specimens were investigated using FESEM. Fig. 3(a) shows the presence of large numbers of voids with unstable surface which is evident that may create less resistance to corrosion in unhardened material. De-passivation occurs in the smaller area of the substrate due to poor interaction of metal substrates which causes defects and pinhole with aggressive ions i.e., electrolyte solution. Therefore, native oxide was forming over the substrate. Due to this reason the electrochemical potential amidst pits exist over the substrate. Largest morphological changes were found like porosity and irregularities in Fig. 3(b). Fig. 3(c) and 3(d) show the hardened and hardened followed by plasma nitrided samples with cracks on the roughed surface. There is absence of voids and porosity due to the bare + hardened + Plasma nitrided sample (EN3) and hardened + hard chromium + plasma nitrided sample (EN4).



**Figure 3.** FESEM images of untreated trials (a) bare material (EN1) (b) bare + hardened material (EN2) (c) bare + hardened+ plasma-nitrided material (EN3) and (d) bare + hardened + hard chromium plated + plasma nitrided material (EN4).



**Figure 4.** EDAX images of (a) bare material (EN1) (b) bare + hardened material (EN2) (c) bare + hardened+ plasma-nitrided material (EN3) and (d) bare + hardened + hard chromium plated + plasma nitrided material (EN4).

There is an increasing passivation element such as Cr and Ni steel matrix corrosion resistance is improved, reported *Kowok* al., [21]. Electrolyte solution interacts with crack propagation [22] the untreated sample damage is larger than that for treated specimen (EN2) EN353. The thickness of the diffused layer is 60 µm. Figure. 4, Shows the EDAX analysis of EN1, EN2, EN3 and EN4 samples with elements presents in the materials to confirming the chemical composition material. In addition, there is an N element presents in EN3 and EN4 confirms the presence of N in the material. From Figure 4, and Table 3, it clearly seen the presence of C, O, N, Mn, Cr, Ni, Fe and Si elements confirms the EN353 untreated and treated samples.

**Table 3.** Detailed elemental composition for EN353 using EDAX after corrosion for EN1, EN2, EN3and EN4.

EN1			EN2			EN3			EN4		
Element	Weigh t%	Atomic %	Element	Weight %	Atomic %	Element	Weight %	Atomic %	Element	Weight %	Atomic %
С	12.86	26.58	СК	49.40	69.46	N	4.82	14.09	Ν	0.63	2.48
0	30.10	46.70	O K	20.09	21.21	0	7.87	20.12	0	1.43	4.94
Na	1.32	1.42	Si K	0.28	0.17	Al	1.09	1.65	Cr	1.94	2.06
Si	1.01	0.89	Cr K	0.77	0.25	Si	1.25	1.82	Fe	3.26	3.22
Ca	0.31	0.19	Mn K	0.60	0.18	Cr	2.37	1.86	Ni	92.74	87.28
Cr	0.50	0.24	Fe K	28.87	8.73	Mn	1.35	1.01	Totals	100.00	
Fe	53.91	23.97	Totals	100.00		Fe	79.51	58.24			
Totals	100.00					Ni	1.74	1.21			
						Totals	100.00				

## 3.3 Microhardness

The Vickers hardness test, as in IS 1501-2008, was done by using MMT-X7-MM5250-X7, Matsuzawa. A 2N indentation load was applied with the dwell time of 10 seconds and with a diamond indenter for the entire test reported in Table. 4. A listed table.4 shows that the profiles of HV before and after plasma nitriding of the samples from the size of indentation HV was conducted [23]. HV values were measured at regular intervals at various three locations on the same sample to find out the hardness values according to Eq. (3).

$$HV = 1.8554 \frac{F}{d^2}$$
 (3)

Where, F is the indentation load (N) and d is the average diagonal length of indentation (mm). The plasma nitrided (EN3 & EN4) sample had shown higher HV than untreated (EN1) and hardened specimen (EN2) samples. The reason for poor hardness to both EN1 and EN2 are due and related directly to the undesired microstructural properties of the materials. The relatively higher hardness value 325 HV was obtained in the sample nitrided due to the existence of hard CrN precipitates in nitrided layer, due to changes in the microstructure properties such as grain refinement and the presence of carbides phase, martensite phases and bainite [18].

S No.	Samples	Average Micro Vickers hardness (HV)
1	Bar substrate (EN1)	$242 \pm 1.06$
2	Hardened specimen (EN2)	279±1.47
3	Hardened + plasma nitrided (EN3)	303±0.91
4	Hardened + hard chromium plated and plasma nitrided	325±0.96
	(EN4)	

**Table 4.** Comparison of un-treated and treated of EN353 samples average micro Vickers hardness by Vickers hardness Method.

#### 3.4 Impact Strength analysis of EN353

The impact strength (Charpy method) of the unprocessed and various processed specimens were carried out and its average values were calculated and listed in Table. 5 for different temperatures. It shows that the EN4 has more impact strength of 123.5 J, while the EN1, EN2, and EN3 have 101.6 J, 115 J and 118.5 J respectively. It is to be noted that the Plasma nitrided sample can be well used for Gear manufacturing due to it's the highest impact strength.

From the Table.5 Impact strength analysis, plasma nitriding of EN353 steel has higher impact strength in all the three different curing temperatures and among the three different temperatures 250 °C, 350 °C, and 450 °C the plasma nitrided EN353 shows better impact strength as 123.6, 124.4 and 124.7 J respectively. However, 450 °C showed somewhat higher impact strength due to the stable and higher heat treatment process.

S.No	Curing Temperature	Materials	Impact strength (J)
1		EN1	101.6
2		EN2	115.0
3	250 °C	EN3	118.5
4		EN4	123.6
5		EN1	109.1
6	350 °C	EN2	115.6
7		EN3	119.5
8		EN4	124.2
9		EN1	111.7
10	450 °C	EN2	116.2
11		EN3	119.8
12		EN4	124.7

**Table 5.** Impact strength of EN353 with different curing temperatures and untreated and treated samples (EN1, EN2, EN3, and EN4).

## 3.5 Tribological Behaviour

Tribological properties of EN353 materials were also found to be significantly influenced by hardening, plasma nitriding and hard chromium plating. Wear losses and friction coefficient of the untreated and the treated EN353 specimen, determined using the pin-on-disc tribometer, and are presented in Table 5. It was detected that the wear losses are quite low and wear volume is drastically decreased from  $241 \times 10^{-3}$  to  $7.42 \times 10^{-3}$  mm<sup>3</sup> with the applied normal load (5N) for all the tested sample materials under same conditions. Compared to the treated specimen, the untreated one had shown higher wear loss in the entire load range thus it might be attributed due to increase in friction coefficient leading to more surface roughness [24]. The friction is contingent on surface roughness, stability and microstructure between Al<sub>2</sub>O<sub>3</sub> ball and EN353 specimen [25]. The wear volume loss was the highest for EN1 and this is significantly reduced to  $15.2 \times 10^{-3}$  which is 15.8 times lesser for EN2 and the same was measured to be 32.1 times lesser in comparison to EN3 against EN1.

**Table 6.** Average friction coefficients, wear volume losses for untreated and treated EN353 specimen(5 N, 1 mm, 25 Hz, 10 min).

S No.	Samples	Average Friction coefficient	Wear volume (V/10 <sup>-3</sup> mm <sup>3</sup> )
1	Bare substrate (EN1)	0.556	241.0
2	Hardened specimen (EN2)	0.451	15.2
3	Hardened + plasma nitride (EN3)	0.331	7.49
4	Hardened + hard chromium plated and plasma nitride (EN4)	0.140	7.42

However the same measurement 32.47 times lesser for EN4 samples in comparison with EN1.At present for automotive gear manufacturing bare+hardened state of samples(EN2) are in use

and including the plasma nitriding as in EN3 and EN4, it will significantly reduce the wear volume loss to half in comparison to hardened state. However, their wear volume losses became closer for EN3 and EN4 specimen. In most cases, the friction coefficient follows initial increase and followed with decrease and it tends to be in a steady state value except for EN4 specimen. For all treated specimen the weight loss decreases with increasing sliding time, but the wear of the untreated specimen is noticed to be higher than that of treated specimen tested under every load condition. This indicates that the wear resistance of treated EN353 surface structure has been improved.

Table 6 shows the wear volume losses and average friction coefficient for untreated and treated specimen under dry conditions. Fig. 5 is drawn for Coefficient of friction in ordinate against time in abscissa. The wear rate was found to be reduced for treated specimen like EN2, EN3 and EN4 specimens due to the formation of surface nitride and secondary phases [26] due to the interaction of Al<sub>2</sub>O<sub>3</sub> ball as a sliding body with the specimen. The figure shows higher value of coefficient of friction for EN1 in comparison to other samples resulting in excessive wear. It is clear that sample EN4 is found to have the least wear due to presence of martensite microstructure which improves the beneficial effect on friction properties [27]. The stability of the curves for EN1 and EN3 specimens is slightly deviated as they show lot of ups and downs indicating that the instability with increasing sliding time. The higher wear loss for EN1 is mainly attributed due to the higher deformation that occurs during wear process as reported by Zandrahimi group [28]. The EN2 specimen curve of Fig. 5 also increases continuously with increasing sliding time. In contrast, the trend of coefficient of friction is steady and stable and low COF value (0.140) with end of wear with lower wear rate for the EN4 specimen.



**Figure 5.** Coefficient of friction versus sliding time obtained for (a) bare material (EN1) (b) bare + hardened material (EN2) (c) bare + hardened+ plasma-nitrided material (EN3) and (d) bare + hardened + hard chromium plated + plasma nitrided material (EN4).

## 3.6 Electrochemical properties

The corrosion test was carried out by electrochemical Potentiodynamic polarization studies. A potentiostat had been engaged to realize the corrosion experiments. EN353 samples with dimension diameter 20 mm and 2 mm thickness were cut for corrosion test. The curves obtained from EIS and Potentiodynamic polarization experiment was used to evaluate the characteristics of the corrosion behaviour of passive films and its nature in the electrochemical processes at their interface.



**Figure 6.** (1) Potentiodynamic polarization curves and (2) Nyquist plots for (a) bare material (EN1) (b) bare + hardened material (EN2) (c) bare + hardened+ plasma-nitrided material (EN3) and (d) bare + hardened + hard chromium plated + plasma nitrided material (EN4).

Table 7	. Detailed	potentiodynamic	polarization	(Ecorr, and Icorr	) and EIS (	(Rct, and Cdl)	) data
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Samples	Ecorr (V)	Icorr (µA cm <sup>-2</sup> )	Rct ( $\Omega$ cm <sup>2</sup> )	Cdl (F cm <sup>-2</sup> )
EN1	-0.706	0.317	407308	6.911e15
EN2	-0.445	0.097	214312	0.9023e-12
EN3	-0.616	0.166	251338	0.1233e-6
EN4	-0.730	0.057	216.8	143929

Three-cell electrode was used in this experiment namely platinum rod as counter electrode, saturated calomel electrode as reference electrode and treated (EN4) & un-treated (EN1) EN353 as working electrode. The electrodes were held at room temperature in 3.5 wt. % NaCl solutions for electrochemical process. The scan rate was done at of 0.1667 mV/s resolution for the electrochemical polarization. The current density ( $I_{corr}$ ) and corrosion potential ( $E_{corr}$ ) can be calculated from the polarization Tafel plot. The frequency range used was in between 0.1 Hz–100 kHz, for the measurement of electrochemical impedance spectroscopy (EIS). The Tafel plot and Nyquist plot for the specimen are added in Fig. 6 (a & b) [29]. The potential corrosion of the convention treated substrate is about -0.616 V. Potentiodynamic polarization and EIS data for Untreated and Treated

EN353 is presented in Table. 7. The  $E_{corr}$  of treated sample is shifted towards the positive side, when compared to the untreated sample [30].

This has been demonstrated to be related to the adsorption capability of chloride ions on the passive film [31, 32]. The positive shift of  $E_{corr}$  (-0.730 V to -0.445 V) shows excellent corrosion resistance for the treated sample. The current density ( $I_{corr}$ ) of treated (EN4) sample shows lesser than that of untreated (EN1) substrate. From the Nyquist plots, it is observed that the charge transfer resistance (Rct) increases while the double layer capacitance (Cdl) values decreases for treated sample than that of the untreated sample. From test results of polarization curves, the protective corrosion efficiency,  $\eta_p$  (%) of the substrate can be calculated using the Eq. (4) [33].

$$\eta_{p(\%)} = \frac{I_{corr}^o - I_{corr}}{I_{corr}^o} X100 \tag{4}$$

Where,  $i_{corr}$  and  $i_{corr}^{o}$  are density associated with corrosion current density and related to the treated and untreated materials, respectively [34]. This obtained data from the electrochemical results suggests that the nitride specimen has excellent corrosion resistance and hence the plasma nitride EN353 steel is well suited for the gear manufacturing sector.

# **4. CONCLUSION**

The EN353 low carbon steel was experimented for bare material (EN1), bare + hardened material (EN2), bare + hardened+ plasma-nitrided material (EN3) and bare + hardened + hard chromium plated + plasma nitrided material (EN4) surface improvement. XRD results divulge that the polycrystalline film for all treated and untreated specimen. Morphological structure of treated EN353 shows absence of pits, voids and presence of voids with excellent bonding with the bare substrate might be a reason to get a better corrosion. In this work, the impact strength and micro-Vickers hardness seem to be more for the plasma treated specimen than that of the untreated specimen. In contrast, the friction coefficient and wear loss volume observed were less for the plasma nitrided EN353. Low friction coefficient and high corrosion resistance of the plasma nitrided specimen are attractive properties as they have resulted in low wear. The corrosion resistance behaviour for plasma treated EN353 (EN4) shows better corrosion resistance and 99.66 % when compared with other specimen in 3.5 wt. % NaCl solutions. The traditionally employed hardening technique for automotive gear manufacturing can be made more effective by plasma nitrided specimen for increasing the life extent of mating gear surfaces in a successful way.

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# References

- 1. P. Schaaf, Prog. Mater Sci., 47(1) (2002) 1.
- A. Vishnu, M. Venkata, M. Venkata Ramana, and K. B. G. Tilak., *Mater. Today: Proc.*, 5(2) (2018) 4192.

- 3. A. Bensely, S. Stephen Jayakumar, D. Mohan Lal, G. Nagarajan, and A. Rajadurai., *Eng. Fail. Anal.*, 13(8) (2006) 1285.
- 4. A. Bensely, L. Shyamala, S. Harish, D. Mohan Lal, G. Nagarajan, Krzysztof Junik, and A. Rajadurai, *Mater. Des.*, 30(8) (2009) 2955.
- 5. Y. Wang, P. Zhang, H. Wu, D. Wei, X. Wei, and P. Zhou., Tribol. Trans., 57(5) (2014) 786.
- 6. F.M. El-Hossary, Surf. Coat. Technol., 150(2-3) (2002) 277.
- 7. S. Ahangarani, F. Mahboubi, and A. R. Sabour., Vac., 80(9) (2006) 1032.
- 8. Diaz-Guillen, J. C., J. A. Diaz-Guillen, E. E. Granda-Gutierrez, M. R. Diaz-Guillen, and M. A. Gonzalez-Albarran., *Int. J. Electrochem. Sci.*, 8 (2013) 973.
- 9. S. Lakshmi Sankar, A. K. Gopal, P. Kuppusami, A. Amala Mithin Minther Singh, M. Prabhu, and S. Muthu Kumar., *AIP Conf. Proc.*, 2311(1) (2020) 070021.
- 10. J. Y. Park, and Y. S. Park., Mater. Sci. Eng. A., 449 (2007) 1131.
- 11. F. M. Bai, X. Ye, H. Y. Zhang, H. W. Zhou, M. Song, Y. X. Sun, and Y. Z. He., *Mater. Lett.*, 255 (2019) 126507.
- 12. R. Mishra, and R. Balasubramaniam., Corros. Sci., 46(12) (2004) 3019.
- 13. A. Chianpairot, G. Lothongkum, C. A. Schuh, and Y. Boonyongmaneerat., *Corros. Sci.*, 53(3) (2011) 1066.
- 14. P. T. Arasu, R. Dhanasekaran, P. Senthil Kumar, and N. Srinivasan., Eng. Sci., 2 (2013) 1.
- 15. Q. W. Ye, Y. Li, M. Y. Zhang, Y. J. Bi, X. P. Gao, and Y. Y. He, Ceram. Int., 46(14) (2020) 22404.
- 16. A. Maniee, F. Mahboubi, R. Soleimani, Met. Mater. Int., 26(11) (2019) 1664.
- 17. S. Lakshmi Sankar, G. A. Kumar, P. Kuppusami, K. Chaitanya, "Importance of Plasma Nitriding Process- A Case study of 40Cr4Mo3 Material", *IEEE* (2019) 421.
- 18. N. Sivanandham, A. Rajadurai, S. M. Shariff, J. Senthilselvan, and A. Mahalingam., *Int. J. Surf. Sci. Eng.*, 11(2) (2017) 118.
- 19. N. A. Astunkar, and A. S. Bonde., Mod. Eng. Res., 4 (2014) 46.
- 20. K. R. M. Rao, C. Nouveau, and K. Trinadh., Trans. Indian Inst. Met., 73(6) (2020) 1695.
- 21. C. T. Kwok, H. C. Man, and F. T. Cheng., Laser Institute of America, 1 (2007) 523.
- 22. U. Kamachimudali, T. M. Sridhar, and B. Raj., Sadhana, 28(3-4) (2003) 601.
- G. B. Ghorbal, A. Tricoteaux, A. Thuault, G. Louis, and D. Chicot., J. Eur. Ceram. Soc. 37(6) (2017) 2531.
- 24. S. Zhang, X. L. Bui, J. Jiang, and X. Li., Surf. Coat. Technol., 198(1-3) (2005) 206.
- 25. C. E. Foerster, F. C. Serbena, S. L. R. Da Silva, C. M. Lepienski, CJ de M. Siqueira, and M. Ueda., *Nucl. Instrum. Methods Phys. Res., Sect. B.*, 257(1-2) (2007) 732.
- N. Kumar, S. Kataria, S. Dash, S. K. Srivastava, C. R. Das, P. Chandramohan, A. K. Tyagi, K. G. M. Nair, and B. Raj., Wear, 274 (2012) 60.
- 27. H. Zhou, C. Wang, Q. Guo, J. Yu, M. Wang, X. Liao, Y. Zhao, and L. Ren., *J. Alloys Compd.*, 505(2) (2010) 801.
- 28. M. Zandrahimi, A. Poladi, and J. A. Szpunar., Wear, 263(1-6) (2007) 674.
- 29. D. Li, J. Wu, S. Lu, B. Miao, W. Cai, Int. J. Metall. Met. Phys., 4 (2019) 031.
- 30. J. Ress, U. Martin, J. Bosch, and D. M. Bastidas., Coatings, 11(2) (2021) 113.
- 31. Y. Xi, D. Liu, and D. Han., Surf. Coat. Technol., 202(12) (2008) 2577.
- 32. H. Jafari, I. Danaee, H. Eskandari, and M. RashvandAvei., *J. Mater. Sci. Technol.*, 30(3) (2014) 239.
- 33. Y. Wang, C. Deng, Y. Sun, X. Shen, and Y. Zhu., Int. J. Electrochem. Sci., 16(7) (2021) 1.
- 34. Y. H. Yoo, D. P. Le, J. G. Kim, S. K. Kim, and P. Van Vinh., *Thin Solid Films.*, 516(11) (2008) 3544.

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