A Comparative Study on the Corrosion Behaviour of Hard Anodic Coatings on AA 6061 Obtained Using DC and Pulsed DC Power Sources

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The corrosion behaviour of the hard anodic coatings prepared by three different methods viz., conventional hard anodizing (C-HA), pulse hard anodizing (P-HA) and low voltage room temperature pulse hard anodizing (LVP-HA) on AA 6061 was compared using electrochemical impedance spectroscopy (EIS) and linear polarisation. Scanning electron microscope (SEM) was used to study the surface morphology before and after corrosion. EIS data revealed that no significant difference in corrosion resistance was observed among three types. R_p , I_{corr} and E_{corr} were found to be highly stable over the exposure period up to 72 h which confirms the excellent corrosion resistance. The studies indicate that the corrosion resistance of LVP-HA and P-HA, which are processed at lower voltage and at relatively higher temperatures, are comparable to that of C-HA which is processed at sub-zero temperatures and high operating voltages. The corrosion resistance of all coatings was found to be improved after hydrothermal sealing.

KEY WORDS: Aluminium; Anodic films; EIS; Polarisation; SEM

1. Introduction

Aluminium and its alloys have tremendous application in the field of space technology and automotive industries. This wide usage is due to their excellent properties, such as high strength-to-weight ratio and good formability. Unfortunately, aluminium alloys are susceptible to corrosion which limits their applications^[1]. Though formation of a natural oxide layer on its surface which is about 2.5 nm^[2] can slightly prevent corrosion, degradation occurs on prolonged storage. Pitting corrosion is the most common type of corrosion encountered in these alloys. In order to improve the corrosion resistance, surface treatments such as anodising can be employed^[2–4].

Anodising, which produces an outer porous array of columnar hexagonal cells normal to the substrate

surface and separated from it by a barrier layer^[5], can offer high corrosion resistance^[6,7]. Conventional anodising of aluminium can build the coating of moderate thickness of 1.8 μm to 25 μm and are known as Type II, as classified by MIL-A-8625, while coatings thicker than 25 μm are known as Type III, hard coat, hard anodising, or engineered anodising. Anodising thickness increases wear resistance, corrosion resistance, electrical and thermal insulation *etc.*^[8]. The hard anodised coatings are of paramount importance in engineering industries where high wear resistant and corrosion resistant surfaces are required such as pistons, cylinders, hydraulic gears *etc.*^[9,10]. Hard anodisation process has also been used in fabrication of sensors due to its insulating properties^[11].

Conventional hard anodising process, which is carried out with dc power supply, requires the processing bath to be controlled at sub-zero temperature in which enormous electrical energy has to be supplied for the refrigeration^[10,11]. Moreover it is associated with the problems like burning and powdering due to low temperature processing and utilization of high

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Table 1 Processing parameters of the all three samples

Process	Temperature (°C)	Current density (A/cm ²)	Duty cycle (%)	Frequency (Hz)	Processing time (min)
C-HA	−5±2	325±10	–	–	80–100
P-HA	10±2	540±10	60–75	5–10	50–60
LVP-HA	25±2	645±10	60–80 (forward), 60–80 (reverse)	10–20 (forward), 400–500 (reverse)	40–60

Note: Processing time varied to get a coating thickness of (60±3) μm ; the electrolyte is 100 mL/L H_2SO_4 + 15 g/L $\text{C}_2\text{H}_2\text{O}_4$

current density. Pulse hard anodising and low voltage room temperature pulse hard anodising, which are processed using DC pulse and pulsed DC with reverse pulse techniques respectively, are carried out at elevated temperatures and therefore these are cost effective. Moreover, the chances of burning is minimised because the voltage applied in pulse and reverse pulse hard anodising is lower compared to conventional hard anodising^[11].

Generally, the corrosion resistance of an anodic film depends on the properties, thickness and integrity of the film. The sealing quality is one of the factors affecting the film properties. The sealing treatment in general enhances the corrosion resistance and the electrical insulating value of the anodic film. Different sealing techniques for the anodic film on aluminium alloys were developed by many researchers. Some sealing techniques have been commonly used in industry, such as hot water sealing, steam sealing, dichromate sealing, nickel acetate sealing and cold nickel fluoride sealing. Boiling water sealing is the simplest and effective one which can prevent the risk of pitting corrosion even in most aggressive atmosphere^[12–15].

In recent years electrochemical impedance spectroscopy (EIS) has become a powerful technique to evaluate the electrochemical behaviour of electrode - electrolyte interfaces. In this technique, a small AC amplitude signal is applied to the system being studied. Therefore, EIS is a non-destructive technique that does not affect the electrode properties to be measured and is suitable for in-situ monitoring of many corrosion processes that occur in wide range of materials, including metallic coatings, anodic coatings and corrosion inhibitors^[3,12,13,16–20]. The corrosion behaviour of anodised layer during exposure to corrosive medium can also be studied as a function of exposure time by EIS^[1–3].

In the present work, the corrosion behaviour of the three different types of hard anodising processes *viz.*, conventional hard anodising (C-HA), pulse hard anodising (P-HA) and low voltage room temperature pulse hard anodising (LVP-HA) were investigated using EIS and polarisation techniques. The main aim of the work was to check the comparability of corrosion behaviour of LVP-HA and P-HA with C-HA so as to make the two former processes an alternative to the latter. Scanning electron microscopy was used to study the surface morphology of the coatings before and after corrosion.

2. Experimental details

2.1 Materials

Aluminium alloy 6061 T6 specimens (composition (wt.%): Mg 0.8–1.2, Si 0.6, Cu 0.28, Mn 0.15, Fe 0.7 and remainder Al balanced) of diameter 24 mm and thickness 4 mm were used in the present study.

2.2 Preparation of hard anodised specimens

The specimens were subjected to cleaning (pre-treatment) before anodisation as per the following sequence.

Ultra sonic cleaning using trichloroethylene at room temperature for 3–5 min.

Alkaline cleaning in the solution with 20–30 g/L Na_2CO_3 , 25–35 g/L Tri sodium ortho-phosphate, 15–25 g/L sodium meta silicate and 1 g/L wetting agent prepared in de-mineralised (DM) water. Cleaning was done using mild agitation for 3–5 min at (60 ± 5) °C followed by DM water rinsing.

Acid de-smutting in the solution with 10–15 mL/L H_2SO_4 , 10–12 mL/L HF and 20–25 mL/L HNO_3 at 20–25 °C for 2–3 min. This was followed by thorough rinsing in DM water.

Hard anodising process was carried out in a lead lined tank which was made as cathode and job as anode. Air agitation was given to the bath with continuous filtration. The process parameters are summarised in Table 1. After hard anodisation some of the samples were subjected to hydrothermal sealing in boiling water for about 30 min to study the effect of sealing on corrosion performance.

2.3 Electrochemical Impedance tests

Corrosion behaviour of the three different hard anodised specimens was monitored using electrochemical impedance spectroscopy (EIS). It was performed using a frequency response analyser (Autolab PG-STAT 302N, Eco-chemie, The Netherlands) driven by Nova 1.4 software. A typical three electrodes cell, Ag/AgCl (saturated with KCl) as reference electrode, a platinum rod as counter electrode and the specimen as the working electrode (1 cm² exposed area) were used in the cell. All the electrochemical tests were conducted in an unstirred, neutral 3.5 wt.% NaCl so-

Fig. 1 Nyquist diagram (a) and Bode plots (b) for unsealed hard anodised samples after 24 h of immersion in 3.5 wt.% NaCl solution

lution at room temperature. Prior to test, the hard anodised samples (both sealed and unsealed condition) were subjected to 24, 48 and 72 h of immersion in 3.5 wt.% NaCl solution to simulate the prolonged/accelerated exposure. The EIS tests were performed with a sinusoidal AC amplitude signal of 10 mV over the open circuit potential (E_{ocp}) in the frequency range from 10 kHz to 0.1 Hz.

2.4 Polarisation tests

To confirm the corrosion results of hard anodic coatings obtained by EIS, polarisation tests were also conducted on test specimens using Nova 1.4 software in the same instrument (Autolab PGSTAT 302N, potentiostat/galvanostat, The Netherlands). The tests were performed at a scan rate of 0.1 mV/s in the applied potential range of -0.250 V to $+0.250$ V with respect to E_{corr} .

2.5 Surface morphology and thickness measurement

The corrosion morphology of the test samples was examined by a scanning electron microscope (LEICA S. 400 I, CAMBRIDGE, UK), and the extent of corrosion after immersion in the corrosive medium was analysed.

Coating thickness measurement was carried out with Fischer ISOSCOPE thickness meter which work on the principle of eddy current.

3. Results and Discussion

3.1 EIS results for the hard anodic coatings without sealing

The most common and standard representation of impedance spectroscopy are Nyquist and Bode plots. The impedance curve of real and imaginary parts is illustrated in Nyquist diagram. Larger the diameter better is the impedance or resistance to corrosion. In

Bode plots, modulus of impedance and phase shift are plotted as a function of frequency over a wide frequency range. The higher intercept of the values of modulus of impedance ($|Z|$) on y -axis shows better resistance towards corrosion. Thus it is from this resulting structure of $Z(\omega)$ vs. frequency response that one derives information about electrical properties of full electrode-material system^[21].

The Nyquist and Bode plots pertaining to the three unsealed hard anodised samples (C-HA, P-HA and LVP-HA) subjected to 24 h immersions in 3.5 wt.% NaCl solution are shown in Fig. 1(a) and (b). Very high impedance curves are observed for all three types of hard anodic coatings. The dimension of the capacitive characteristic curve for C-HA is slightly greater as compared to that of P-HA and LVP-HA samples. Thus the corrosion resistance of the hard anodic coatings decreases in the order C-HA > P-HA > LVP-HA. This could be due to the difference in the size and density of the pores among three types of samples. One of the reasons for porosity difference is the solvation effect of the electrolyte. This effect is lower in C-HA than those of P-HA and LVP-HA. However, there is no significant difference in R_p values of three samples *i.e.*, the values are all in same order ($10^6 \Omega \cdot \text{cm}^2$) as summarised in Table 2. Higher R_p value represents better corrosion resistance^[22]. R_p values exceeding $2 \times 10^5 \Omega \cdot \text{cm}^2$ are considered to be properly anodised samples for common applications^[23]. Absence of inductive loop suggests that no localized corrosion has taken place^[24]. The high impedance towards low frequency is characteristic of good corrosion resistance^[25,26]. From the Bode plot in Fig. 1(b), it is clear that higher impedance values are observed on approaching lower frequency which indicates that the coating is highly compact and no major penetration of the corrosive medium has taken place. The advantage of Bode plot is that the data for all the measured frequencies are shown and also a wide range of impedance values are displayed. In the Bode diagram the values of $|Z|$ and

Table 2 EIS data of hard anodic coatings after immersion in 3.5 wt.% NaCl solution

Immersion time (h)	CPE (10^{-7} F/cm ²)			R_p (10^6 Ω ·cm ²)		
	C-HA	P-HA	LVP-HA	C-HA	P-HA	LVP-HA
24	1.48 (0.322)	2.07 (0.586)	3.42 (0.83)	10.7 (49.5)	7.6 (27.16)	4.6 (19.18)
48	2.11 (0.488)	3.08 (0.819)	3.84 (1.11)	7.5 (32.6)	5.16 (19.4)	4.1 (14.3)
72	3.07 (0.848)	3.51 (1.434)	4.59 (2.365)	5.1 (18.77)	4.5 (11.1)	3.5 (6.7)

Note: values in the brackets are for the sealed specimens

Fig. 2 A possible equivalent circuit for hard anodised coating for aluminium alloys

frequency are plotted in the logarithmic scale. The impedance curves from Nyquist plot and Bode plots show the typical curve for highly corrosion resistant coating where no Warburg or diffusion control reaction has taken place. Hence, it can be concluded that there is no significant deterioration in initial stage of immersion (up to 24 h) in aggressive medium (3.5 wt.% NaCl).

The possible equivalent circuit for this type of the hard anodic coatings can be proposed as $[R_1Q_1(R_2Q_2)]$ in circuit description code (CDC) in which elements within the bracket are connected in parallel. The equivalent circuit which gives the best fitting for all the plots is shown in Fig. 2. R_p values obtained from the Bode plots at the least frequency (0.1 Hz) are approximately same as that observed in the electrochemical circle fit.

Since the outer layer is much thicker than inner barrier layer for hard anodic coatings, the capacitive

characteristic line (inset in Fig. 1(a)) which is nearly normal to Z_{re} axis is observed at high frequency region in Nyquist plots (Fig. 1(a)). This region is simulated as Q_1 , constant phase element (CPE), for thicker outer layer. R_1 represents the solution resistance. Q_2 and R_2 are the CPE and resistance for barrier layer respectively.

Figs. 3, 4 and 5 represent Nyquist and Bode plots for different immersion periods (24, 48 and 72 h) for C-HA, P-HA and LVP-HA samples respectively. The results of 24 h immersion are already discussed above. Further immersion up to 48 h in the corrosive solution, identical impedance spectra are observed and there is only slight decrease in the capacitive arc as indicated by the Nyquist plots for all the samples. Hence a very little change in R_p values is found with increasing the immersion time up to 48 h.

The oxide coating has heterogeneities that make the capacitive behaviour better simulated by constant phase elements (CPE) than by simple capacitances (C). CPE and R_p values are summarised in Table 2. CPE is also an important parameter in impedance studies and is defined as

$$CPE = 1/(j2\pi fC)^n \quad (1)$$

where f is frequency, n is the frequency dispersion factor that varies from 1 to 0. Only when $n=1$, CPE is considered to be real capacitance. Better the uniformity or corrosion resistance of the coating lower is the value of CPE^[1,4]. The CPE values for all the samples lie between 1.48×10^{-7} and 4.59×10^{-7} F/cm². There

Fig. 3 Nyquist diagram (a) and Bode plots (b) for unsealed conventional hard anodised (C-HA) specimens for different immersion periods of 24 h, 48 h and 72 h

Fig. 4 Nyquist diagram (a) and Bode plots (b) for unsealed pulse hard anodised (P-HA) specimens for different immersion periods of 24 h, 48 h and 72 h

Fig. 5 Nyquist diagram (a) and Bode plots (b) for unsealed low voltage and room temperature pulse hard anodised (LVP-HA) specimens for different immersion period of 24 h, 48 h and 72 h

is an increase in the values over the exposure periods. C-HA has the CPE values increase from 1.48×10^{-7} to 3.07×10^{-7} F/cm². Similarly P-HA shows the CPE values to increase from 2.07×10^{-7} to 3.51×10^{-7} F/cm². LVP-HA has the same trend in which the values raise from 3.42×10^{-7} to 4.59×10^{-7} F/cm². The result reflects that uniformity of the coatings is losing slightly over the exposure periods. The decrease in impedance and increase in CPE values observed with respect to immersion time can be attributed to the slight dissolution of the porous layer.

The Bode modulus of all three types of the hard anodised samples are depicted in Figs. 3(b), 4(b) and 5(b) which show the impedances towards low frequency are almost similar even after 48 h of immersion comparing to their respective 24 h immersion. This infers that all the hard anodised coatings do not undergo major damage. On prolonged immersion up to 72 h, there is no drastic drop in R_p values, though some slight decrease in the values are observed due to infiltration of corrosion medium into the cracks and defects of the outer oxide layer. Fig. 6 represents the

change in R_p as a function of immersion time for the unsealed samples. The slopes are gradually decreasing without steep changes which indicate that there is no rapid decrease in R_p on increasing immersion time up to 72 h. The R_p values for C-HA decreased from 10.7×10^6 to 5.1×10^6 Ω·cm². P-HA has the R_p values from 7.6×10^6 to 4.5×10^6 Ω·cm² and R_p values for LVP-HA were found to decrease smoothly as compared to the other two. Though the values decrease over the exposure periods, but this decrease is not significant. It suggests that all three hard anodised specimens show good resistance to corrosion in which C-HA exhibits slightly better corrosion resistance than P-HA and LVP-HA.

3.2 Polarisation result for unsealed coatings

Since corrosion is an electrochemical phenomenon, linear polarisation can be used to provide the important information on corrosion rate, corrosion current *etc.* In this technique, a current-potential relationship graph is obtained by scanning the specimen through a potential range that is very close to corrosion po-

Table 3 Polarisation data of hard anodised specimens after exposure to 3.5 wt.% NaCl solution

Immersion time (h)	E_{corr} (V)			i_{corr} (10^{-8} A/cm ²)		
	C-HA	P-HA	LVP-HA	C-HA	P-HA	LVP-HA
24	−0.541	−0.625	−0.739	1.07	1.11	2.26
48	−0.584	−0.629	−0.382	1.18	1.75	3.19
72	−0.596	−0.723	−0.852	2.91(0.134)	3.84(0.28)	4.41(0.42)

Note: values in the brackets are for the sealed specimens

Fig. 6 Variation of polarisation resistance as a function of immersion time for unsealed samples

tential (E_{ocp} or E_{corr}). E_{ocp} is the potential characteristic of the specific metal-solution with respect to a coupled reference electrode when no external current is supplied. The polarised graph is called Tafel plots ($\lg i$ vs. potential), which comprise of anodic curve and cathodic curve. The corrosion current density, i_{corr} , is given by the Stern Geary equation as given below^[27]:

$$i_{\text{corr}} = \frac{(\beta_a)(\beta_c)}{2.303(\beta_a + \beta_c)R_p} \quad (2)$$

where i_{corr} is corrosion current density (A/cm²), β_a is anodic Tafel slope (V/decade), β_c is cathodic Tafel slope (V/decade), R_p is polarisation resistance (Ω).

i_{corr} value depicts important information regarding the corrosion behavior of the specimen surface. The larger the i_{corr} value, the higher the active corrosion is.

The E_{corr} of bare specimen is -0.8664 V with respect to Ag/AgCl reference electrode^[21]. The hard anodised samples show positive corrosion potential when compared to bare aluminium as shown in Table 3. Thus a nobler electrode potential is observed for the hard anodic coatings compared to bare substrate. On exposure to the corrosive medium up to 72 h, a little change in the corrosion potential is observed for all the samples. The E_{corr} values for C-HA are stable as compared to P-HA and LVP-HA. A slight fluctuation in the E_{corr} values is recorded for P-HA and LVP-HA over the exposure time. A more stable potential is seen for C-HA which is towards positive potential than those of P-HA and LVP-HA. The nobler E_{corr} values for C-HA suggest the higher corrosion resistance of the coating. As it was

Fig. 7 Polarisation curves for different immersion periods 24 h (a), 48 h (b) and 72 h (c) for C-HA, P-HA and LVP-HA

emphasized by Cao^[23], the corrosion resistance cannot be evaluated by free E_{corr} alone. Free E_{corr} mainly describes the thermodynamic property of the material. It is scientific to evaluate the corrosion behaviour by estimating the i_{corr} to support the corrosion behaviour obtained from E_{corr} .

Fig. 7 illustrates the Tafel plots of C-HA, P-HA and LVP-HA as a function of immersion period in

Fig. 8 Corrosion current density as a function of immersion time for unsealed hard anodised specimens

NaCl solution. Most of the plots show absence of sudden current increase in the polarisation curves, which confirm the non-occurrence of pitting^[12]. Fig. 8 illustrates i_{corr} as a function of immersion period for the hard anodised coatings, as evaluated from Fig. 7. The i_{corr} values for all the unsealed hard anodised specimens are very low (in the order 10^{-8} A/cm²) as summarised in Table 3. The test results, *i.e.*, i_{corr} values are comparable with the values reported earlier^[21]. For 24 h immersion, C-HA shows slightly lower i_{corr} value than that of P-HA and LVP-HA. This indicates C-HA is slightly more passive to corrosion. However, the difference in i_{corr} values among three specimens is minimal. The trend is in good agreement with that observed in EIS data.

Continuation of the immersion in corrosive medium doesn't show significant change in the i_{corr} value as indicated in Fig. 8. Hence, on immersion up to 72 h, no major active corrosion has taken place. However, as expected a slight and gradual increase in corrosion on continuous exposure to corrosive medium is seen due to penetration of the medium into the pores.

3.3 Effect of sealing on corrosion behaviour

Fig. 9 depicts the effect of sealing on hard anodic film. The studies are conducted on unsealed and sealed hard anodized samples immersed in 3.5 wt.% NaCl solution for 24 h, 48 h and 72 h duration. The dimensions of capacitive arcs have increased for the sealed hard anodized samples.

R_p values of sealed specimens have improved as compared to unsealed samples in all the cases as presented in Table 2. For C-HA, R_p values have raised from 10.7×10^6 to 49.5×10^6 $\Omega \cdot cm^2$. The R_p values for P-HA have also found to increase from 7.6×10^6 to 27.16×10^6 $\Omega \cdot cm^2$. Similarly the R_p values for LVP-HA have enhanced from 4.6×10^6 to 19.18×10^6 $\Omega \cdot cm^2$. Thus, corrosion resistance of the hard anodised samples is further enhanced on subjecting to hydrothermal sealing. A reasonable explanation

Fig. 9 Nyquist plots to illustrate the effect of sealing for C-HA (a), P-HA (b) and LVP-HA (c)

for the increase in corrosion is that during sealing process in boiling water, various forms of hydrated alumina are produced. The following sealing reaction occurs at temperature above 80 °C.

Boehmite is the major hydrated alumina formed besides aluminium hydroxide. The hydrated alumina expands and occupies greater volume and micro-pores in the porous anodised film are filled with it^[12,28]. Thus the penetration of chloride ions, water and oxygen are retarded giving rise to better corrosion resistance. The values of i_{corr} for all the sealed hard anodised specimens also decrease by an order of 1 as

Fig. 10 SEM micrographs of sealed C-HA: (a) before immersion; (b) after immersion of 72 h

Fig. 11 SEM micrographs of sealed P-HA: (a) before immersion; (b) after immersion of 72 h

Fig. 12 SEM micrographs of sealed LVP-HA: (a) before immersion; (b) after immersion of 72 h

given within parentheses in Table 3. This is in a good agreement with the trend observed in impedance studies.

3.4 Analysis of damage function

The damage function (D) is based on the change in impedance in low frequency region. It is an important parameter characteristic of corrosion behaviour^[29,30]. The damage function is

$$D = \lg(Z_0/Z_t)_{0.1\text{Hz}} \quad (3)$$

where Z_0 and Z_t are impedance values respectively at $t=0$ and $t = t_{\text{corr}}$ (72 h in the present study). When

$D=0$, the specimen shows a perfect corrosion resistance. Increase in D value shows decrease in corrosion resistance. The D values of C-HA, P-HA and LVP-HA under unsealed condition are 0.322, 0.218 and 0.118 respectively. This shows the change in Impedance for LVP-HA is lower on immersion upto 72 h as compared to that of C-HA and P-HA.

3.5 Corrosion morphology

Microcracks, also called crazing, which are typical and characteristic of hard anodised surfaces, are observed on all three types of as prepared hard anodic coatings (Fig. 10-12). SEM micrographs of the samples taken after immersion for 72 h in corrosive me-

Fig. 13 SEM micrograph of a corrosion spot on unsealed C-HA after 72 h immersion

dia revealed initiation of corrosion around the pores. This may be due to meager penetration of corrosion solution through these micro cracks of anodic coating. LVP-HA shows more prominent micro cracks after 72 h of immersion than the other two. This may be the possible reason for the slight decrease in the impedance value of LVP-HA as compared to that of P-HA and C-HA. However, major pitting corrosion is not observed in any of the three hard anodised samples.

For unsealed hard anodised specimens, few corrosion spots were observed under visual inspection as given in Fig. 13. A closer examination of the corrosion spots using SEM shows deposition of granular corrosion product. Thus it can be concluded that hydrothermal sealing of the hard anodised samples can prevent crevice corrosion and also degradation by chloride ion attack can be retarded.

4. Conclusions

Corrosion behaviour of three different hard anodic coatings *viz.* conventional, pulse and low voltage room temperature pulse hard anodisation (C-HA, P-HA, LVP-HA) on AA 6061 was investigated using electrochemical impedance spectroscopy (EIS) and linear polarisation techniques.

Very large impedance curves were obtained for all three hard anodic coatings on exposure to corrosive 3.5 wt.% NaCl solution. The large dimensions of capacitive arcs and impedance values reflect the high corrosion resistance of all the samples. Though there is no significant difference in the corrosion resistance among three samples, the corrosion resistance of the unsealed specimens was found in the order C-HA > P-HA > LVP-HA. Further upon immersion up to 72 h, no remarkable change in R_p values was found. This is shown by the identical impedance spectra which were recorded during the immersion periods confirming the coatings are stable and intact.

E_{corr} values were generally found to be stable though there were some minor fluctuations. There were little increases in i_{corr} values over the exposure

periods which can be attributed to the slight dissolution of outer porous layer. SEM micrographs revealed minor degradation and corrosion had just initiated around the pores and cracks after 72 h of immersion. LVP-HA samples showed more prominent micro cracks after 72 h of immersion than the other two samples.

From the damage function analysis, D is lower for LVP-HA than that of P-HA and C-HA which illustrates change of impedance as a function of immersion time is lower for LVP-HA than those of P-HA and C-HA.

After hydrothermal sealing, the R_p values for all the specimens have further improved which was shown by increase in the dimension of the impedance arc. Post sealing corrosion resistance of all three types of hard anodised samples follow the same trend as seen in the unsealed condition. In this case also there was no significant difference in the R_p values of coatings obtained with different processes. A very little change in impedance spectra were observed on exposure periods in corrosive medium. Thus, from the overall results it can be concluded that LVP-HA and P-HA have corrosion behavior comparable to that of C-HA.

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