Tribological Behavior Of Electrocodeposited Nano Composites On Magnesium Alloys Using Direct And Pulse Current – A Review

D. Peter Pushpanathan, Dr. N. Alagumurthi, Dr. S. Pradeep Devaneyan

Abstract: Coating on magnesium alloys continues to remain as a great challenge because of its highly reactive nature. Although many conventional surface treatment methods are available, electrocodeposition is still considered to be the most versatile and economical procedure. This article extensively discusses about various pretreatment procedures for magnesium alloys and the effect of current waveforms on the tribological characteristics of coatings. Most of the literatures available today focus on the investigation of the behavior of the coatings prepared by direct current. Very limited literature is available on the coating of magnesium alloys using pulse current. In this article, an in depth analysis and comparison has been done between the aspects of the composite coatings produced using direct current and various wave forms of the pulse current. From this review it is understood that pulse current is capable of producing more efficient coatings and functionally graded coatings could be obtained by controlling the waveforms. From this review, it is learnt that the potentiality of waveforms in electrodeposition could be explored further to produce durable surface composite coatings on magnesium alloys.

Keywords: Magnesium alloy, electrocodeposition, pretreatment, direct current, pulse current, waveforms

1. INTRODUCTION
Magnesium alloys are widely used in the cockpit instrument panels, engine components, rudder pedals, gear boxes, etc. of the aircraft [1]. They are the most preferred metal in the automobile industry as well for their light weight and easy formability. However the applications of magnesium alloys are restricted to a few areas due to inferior surface hardness, wear resistance and corrosion resistance. Hence several techniques such as micro arc oxidation, conversion coatings, organic coatings, physical vapor deposition, chemical vapor deposition, electroplating, etc. have been adopted to enhance the surface properties of magnesium alloys [16, 46]. Laser cladding was used to deposit nano composite layers on AZ80 magnesium alloy and it resulted in the production of complex intermetallics [2]. Micro arc oxidation (MAO) was used with a laser shock peening pretreatment alloy to coat hydroxyapatite bio composite coating on AZ80 magnesium [36, 38]. Electroplating is a proven eco-friendly, economical and efficient technique used for plating magnesium alloys [47, 50]. Electrocodeposition is a technique used for fabricating surface composites by incorporating hard phase reinforcements such as SiC, TiC, Al2O3 WC on to the surface of the substrates [12]. Extensive research work has been done on enhancing the surface properties of magnesium alloys using these reinforcements. Properties such as microhardness, wear resistance and corrosion resistance of the substrate have been improved by incorporating nano and micro reinforcements with copper and nickel matrix. However, stringent pretreatment procedures are to be followed before initiating the electrodeposition process. It is important to remove the porous oxide film on magnesium before subsequent coating [24].

As magnesium alloys such as AZ91, AZ31 and AZ80 contain α and β phase which are of anodic and cathodic nature respectively, it is critical to apply an undercoat for obtaining an equipotential surface [32]. Usually the pretreated substrate is coated with zinc and later with copper before being coated with Nickel. Nickel is widely selected for coating magnesium alloys due to its excellent hardness and corrosion resistance properties. Various pretreatment procedures adapted for magnesium alloys are discussed in depth in this article. The effect of reinforcements and plating parameters on the properties of the electrodeposited coatings are analyzed for direct current and pulse current. Although, decent number of literatures are available on the electrodeposition of nickel composites on magnesium alloys, very limited work is found to have been done using pulse current. Pulse current is found produce coatings with better characteristics as compared to its counterparts produced by direct current. Due to the instantaneous variation in the current and the time of relaxation, durable coatings with better structure and properties are produced [55]. The characteristics of composite coatings produced by various waveforms such as square, triangular, ramp up and ramp down are discussed in detail.

2. MAGNESIUM ALLOY PRETREATMENT TECHNIQUES
Electroplating magnesium is a challenging process due to the tendency of magnesium to readily form oxide and hydroxide films when exposed to the atmospheric conditions. These films are porous and prevent further electrodeposition by exhibiting poor conductivity and adhesion. Hence it is important to remove this oxide layer before further plating [21]. Many attempts were made on AZ31, AZ61 and AZ91 magnesium alloys to develop an ecofriendly and efficient pretreatment process. All pretreatment processes start with pickling with diluted hydrofluoric acid, hydrochloric acid, phosphoric acid, Nitric acid, Sulphuric acid, etc. in mild concentration for a few seconds. This treatment removes the thin oxide film on magnesium exposing the metal. However, careful control of

• Research scholar, Pondicherry Engineering College, Department of Mechanical Engineering, Pondicherry, India
• Professor, Pondicherry Engineering College, Department of Mechanical Engineering, Pondicherry, India
• Professor, Christ College of Engineering and Technology, Department of Mechanical Engineering, Moolakulam, Puducherry -605010, India.
the time and concentration of the treatment is necessary to avoid excessive etching of the metal surface. In AZ91, the etched sample is activated in an alkaline bath containing potassium pyrophosphate, sodium carbonate and potassium fluoride at room temperature for 3 minutes in order to prepare the specimen for further zinc immersion coating. This is done in order to improve the adhesion of zinc coating on the surface of the specimen. AZ91 magnesium alloy is characterized by two phases viz; α and β, which are anodic and cathodic in nature. This leads to the non-uniform deposition of zinc. Therefore, in the pretreatment of AZ31, a trace of copper ions were added to the activation bath to act as sites of nucleation for subsequent deposition of zinc. Zinc coating prevented re-oxidation of magnesium and promoted charge transfer capability of nickel ions producing adherent, uniform and compact coating. Copper coating was directly applied on AZ31 from copper hydroxide with 0.5 – 3 A/dm² current density. Uniform and dense copper layer was obtained [30, 35]. The time of zincating plays a major role in deciding the quality of the subsequent copper or nickel coating [40]. Therefore hydrofluoric acid activation followed by optimization of zincating period was done on AZ91D magnesium alloy [13]. However, in the same experiment, cyanide bath was for depositing copper over zinc. As cyanide is hazardous, various alternatives such as pyrophosphate and alkaline baths were proposed [50]. Double zincating followed by electroleless nickel phosphorous coating could be used as an undercoat for subsequent nickel electrodeposition [29]. Galvanostatic etching technique was also used to obtain an equipotential surface before applying copper layer on AZ80 magnesium alloy. Galvanostatic etching done at an anodic current density of 20 mA/cm² for 120 seconds was adopted instead of zinc coating [16, 18, 19, 31, 48]. The effect zinc leaching and concentration of copper salts in coating Mg-Li alloys were studied [14]. An effective pretreatment process with citric acid was attempted on AZ91D alloy for obtaining and equipotential surface [43]. Polarization effect of activation and zincating processes while coating AZ31 magnesium alloy with aluminium in ionic electrolytes were studied [15]. The influence of time of zinc immersion and fluoride addition was studied. It was found that the optimum time of zincating is 30 seconds. Fluoride forms a loose MgF₂ film in the zincating bath which affects the adhesion of subsequent nickel deposition [1, 52]. Addition of trace SnCl₂ resulted in an adherent, corrosion resistant and smoother nickel coating [20]. Copper depositions on AZ31 magnesium alloys were obtained by direct plating of copper without any pretreatment. A dense coating of copper with a reasonable stability and adhesion was obtained in the presence of additives of citrate and fluoride salts [32]. AZ91 magnesium alloy was etched first in a mixture of nitric and phosphoric acid. Then the substrate was subjected to electroleless nickel plating for 60 minutes. This sample was further electroplated with Cu-Zn film [26]. While electroplating copper on AZ31, an organosilicon heat resistant varnish was used as an interlayer. The interlayer was then sensitized with stannous chloride and activated with silver nitrate [33]. A new pickling combination of hydrochloric and hydrofluoric acids was formulated for the application of stannate conversion coatings on AZ91 [39]. A two step zincating procedure was investigated in coating AZ91 with nickel. It was found that a thin film of phosphates and fluorides deposited on a phase during the first zinicate treatment and the deposition of zinc on the β phases was enhanced in the subsequent zinckating process. These films protected the magnesium surface from being corroded during the coating process [41]. Alternate pickling in strong citric acid followed by an alkaline and weak citric acid treatment yielded equipotential surfaces by dissolving the magnesium rich α phase and then aluminium rich β phase in case of AZ91 magnesium alloy [51]. From the above discussion, it is understood that extensive research has been done on the electrodeposition of AZ91 cast alloy and the wrought alloy AZ31. However, very limited literature is available on the electrodeposition of the high strength AZ80 magnesium alloy.

3. ROLE OF REINFORCMENTS IN ENHANCING THE COATING CHARACTERISTICS

Reinforcements are the hard phase ceramic particles added to the matrix of the coated metal, in order to enhance the surface properties such as hardness, wear and corrosion resistance. The effect of nano SiC particles in spherical and rod forms embedded in Ni-W-P matrix was studied. It was concluded that the coating characteristics showed significant improvement regardless of the particle shape [17]. Silicon carbide ranging from 5 g/l to 20 g/l were added to Watts nickel coating bath. SiC particles of size from 2 to 3 µm were electrodeposited and it was found that the properties improved up to 15 g/l of reinforcement and deteriorated beyond that. The change in crystal structure of the coating after the addition of nano SiC particles along with saccharin to the watts nickel coating batch was studied. It was found that the addition of nano SiC particles altered the texture of the coating significantly [8]. The effect micro and nano powders of SiC on the coating characteristics showed that micro sized particles had more negative zeta potential compared to the nano particles. Hence it was easier to codeposit micro SiC than the nano particles which yielded a rougher surface. Also, the amount of SiC particles deposited decreased with the stirring speed in case of micro and it increased in case of nano particles [7]. SiO₂ particles along with nickel were deposited on to AZ91HP magnesium alloy. The nano composite coatings exhibited significant improvement in the hardness and wear resistance due to grain refinement and dispersion strengthening effect [11]. Boron carbide and boron nitride reinforcements were along nickel from Watts nickel bath. Three component Ni-BN and Ni-B₄C composites produced by electrodeposition resulted in superior microhardness [3]. Ni-B nano crystalline coating containing 4.38% B₄C was fabricated and the hardness increased exponentially to a maximum of 954Hv as compared to 245 Hv of Nickel. The percentage of boron carbide incorporated in the Ni matrix was found to decrease with an increasing current density [4]. Codeposition of ultrafine powders of Al₂O₃, ZrO₂ and SiC was done along with Ni. It was found that the grain size and structure of nickel was altered by changing the current density and pH of the bath. It was also understood that the aluminium oxide and zirconium oxide powders can be deposited without any additive. However, trivalent complexing ions of Cobalt enhance the rate of deposition of SiC particles[6]. Superior coatings with high hardness and corrosion resistance were produced by incorporating TiC in...
Ni matrix. The grain size of nickel was reduced as a result of introducing TiC particles in the bath [5,67]. Intercrystalline deposition of TiC particles and dispersion hardening effect were found to influence the microhardness of the coatings. TiC coatings successfully fabricated with a non aqueous electrolyte, N-methylformamide resulted in hydrogen free coatings with high microhardness[66-69]. From this analysis we understand that the second hard phase ceramic particles by and large result in grain refinement of nickel matrix and improvement in the microhardness of the composite coatings. However there are other parameters such as current density, stirring speed, type of current, percentage incorporation of reinforcement particles, etc. which contribute to the enhancement in the coating characteristics such as microstructure, microhardness, wear resistance and corrosion resistance etc. The following sections will be utilized to analyze the effect of direct current and pulse current waveforms on the aforementioned coating properties.

4. EFFECT OF DIRECT CURRENT ON THE PROPERTIES OF THE COATINGS

Electrocodeposition is an adaptation of conventional electroplating process where the second phase hard particles are incorporated along with a metal matrix on to the surface of the substrate. Current is used to drive the dissolved particles of anode in the solution towards the cathode which is the substrate. Many models are available to define the mechanism and kinetics of this coating process out of which the most discussed one is the Guglielmi’s two step model [57]. Direct current is obtained by using a rectifier which converts AC to DC. The direct current flows continuously in one direction and the voltage is stepped down using a transformer. Of the electrocodeposition process parameters such as current density, pH, stirring speed, stirring time, coating time, distance between the electrodes, temperature of the bath, etc., current density plays an influential role in determining the morphology of the coating which in turn modifies its properties. Higher coating current density leads to increased rate of deposition and adhesion of the coating with the substrate. Higher deposition rates result in loose non-adherent coatings. Current efficiency gives an idea of the current actually utilized for depositing the metal as compared to the total current supplied. Homogenous incorporation of reinforcements can be controlled by adjusting the stirring speed. The effect of various process parameters especially, the DC current density is discussed in the ensuing topics.

4.1 Microstructure and microhardness of the coatings

AZ91D magnesium alloy was first coated with zinc by immersion and then with nickel by electrodeposition in a bath containing nickel sulphate, di ammonium fluoride and tri ammonium citrate. Coating was done in a 3 cell electrode at a temperature ranging from 45–55°C, with a cathodic current density of 2.0–3.5 A dm⁻² for a duration of 20-25 mins. A compact coating of nickel was obtained on AZ91D substrate by adjusting the percentage of Fluoride ions in the bath. The scanning electron micrograph is characterized by the presence of nodular, cauliflower like arrangement of nickel as shown in Fig.1 [36].

Electrodeposition of nano crystalline nickel was done on AZ91 magnesium alloy. Pretreatment steps of pickling with hydroflouric and hydrochloric acid was done. Pickling followed by activation, zincating and electrodeposition of copper were carried out on the substrate before being coated with nickel [54]. Copper was coated with a current density of 8maCm⁻² in an alkaline bath for 1000 seconds. Then the copper coated sample was transferred to watts nickel bath where it was further coated with nickel at a current density of 50maCm⁻² for 600 seconds. The SEM image of the microstructure of AZ91 is given in Fig. 2(a), which is characterized by the presence of α and β phases. Current density and bath constituents were adjusted to obtain a nickel coating of 95 nm grain size as shown in Fig. 2. (b). Improvement in the microhardness values up to 204 Hv was noticed as compared to 73 Hv of magnesium alloy [25].
The effectiveness of galvanostatic etching before plating copper over AZ31 magnesium alloy was studied. An eco-friendly copper plating bath was used with a current density of 24 CCm$^{-2}$. The sample with only mechanical grinding produced uneven coating exposing magnesium in some places as shown in Fig 3(a). This results in the formation of oxides and hydroxides of magnesium which led to poor conductance of the coating. However, these oxides are removed completely by galvanostatic etching which helped in achieving pore free homogenous coating as shown in Fig 3(b) [29].

Copper was directly electroplated on AZ31 alloy in a copper hydroxide bath with citrate and fluoride ion at a current density of 1.5 Adm$^{-2}$ for 30 minutes. A dense copper coating with nodular spherical structure without porosity was achieved. The coating appearance and quality appeared to deteriorate with rising current density. The citrate complexing agent and the fluoride ions retarded the dissolution of magnesium ions thus producing durable base copper coatings for further nickel electrodeposition [52].

4.2 Wear resistance
AZ91 was initially coated with copper in an alkaline bath and then coated in an eco friendly copper bath with a current density of 4 Adm$^{-2}$ for 300 seconds. This sample was further electroplated with trivalent chromium using direct current. Wear test results given in Fig 4(a) indicate significant improvement in wear resistance of the copper coated samples as compared to the uncoated AZ91D.
Fig. 4. (a) Weight loss comparison of uncoated, as plated Cu-coated, as plated Cu/Cr coated and flame healed samples and (b) Worn surface morphology of Cr/Cu specimen (c) SEM of the wear tested surface and EDS results at A and B locations in the SEM image.

Portion A of the worn surface morphology shown in Fig.4 (b) indicates a strong presence of chromium in the EDS analysis report shown in Fig.4(c). Accordingly the SEM image in A indicates less deformation. Hence it was confirmed that the wear loss was greatly minimized due to the high hardness imparted by the copper-chromium coating. However B indicates wear tracks and the corresponding EDS results confirm the presence of more iron resulting in a decline in the hardness and wear resistance [34].

4.3 Corrosion
Hydrophobic coating of CuO deposited on AZ91D magnesium alloy, exhibited excellent corrosion resistance. An alkaline sodium potassium tartarate bath was employed with a pH of 13-13.5, and current density of 600 mA dm⁻². Potentiodynamic polarization study shown in Fig 5, exhibited more positive E_{Corr} value and less I_{Corr} values for the coated sample when compared to the bare magnesium substrate [26, 42, 45].

A trace of copper ions were added in the activation bath and subsequent zinc coating was done. The copper ions acted as a seed for zinc nucleation by creating an equipotential surface on the biphasic AZ91 magnesium alloy. Copper electrodeposition was done in an alkaline bath of pH 13.5 at room temperature for 1000 seconds with a current density of 8 mA cm⁻². Uniform nickel coating was applied over the copper undercoat with a current density of 50 mA cm⁻². Activation bath with copper ions yielded compact film with excellent adhesion and corrosion resistance as shown in Fig 6.

Fig. 5. Potentiodynamic polarization test results

The anodic polarization curves of uncoated and coated samples of AZ31 shown in Fig. 7 indicate that coatings with dual copper deposits and a nickel layer have superior corrosion resistance than its counterparts. These samples exhibited higher corrosion potential and lower corrosion current density. The highest corrosion potential of -0.25 V and lowest corrosion current density of 2x10⁻⁵ A cm⁻² was found to be present in the sample coated with nickel. From the above examples, it is understood that nickel with a copper undercoat improves the corrosion resistance of magnesium alloys [29, 37, 49]. Direct nickel electrodeposition was carried out on AZ31 magnesium alloy where the dissolution of magnesium was contained by fluoride film generated by the KF present in the bath. Crack free coatings of nickel produced by reduced hydrogen evolution improved the corrosion resistance of the magnesium alloy [28].
The phosphorous content of Ni-P coated AZ91D magnesium alloy decreased with the increasing current density and vice versa. At low current density, the coating seemed to be compact and amorphous. However, the higher phosphorous content in the coating resulted in higher corrosion current ($I_{corr}$) and therefore resulted in poor corrosion resistance [60].

5. EFFECT OF PULSE CURRENT ON THE PROPERTIES OF THE COATINGS

Pulse current electrodeposition has the ability to produce fine grains by increasing the rate of nucleation. Unlike direct current, the pulse current has three variables, (i) pulse on time (ii) pulse off time and (iii) peak current which are controlled independently to achieve the desired texture. The change in amplitude, polarity and duration in the current and potential effected by the waveforms used in the pulse current yield coatings with a different crystal structure as compared to the ones produced by direct current. During the ON time, ions move towards the depleted zone and deposit uniformly on the part. The layer next to the cathode is discharged during the OFF time enabling the particles in suspension to deposit on the cathode. Sudden increase in instantaneous peak current helps in producing finer grains due to the higher overpotential. The effect of process parameters such as current density, frequency, on/off time on the morphology, corrosion resistance and thickness of the coatings were studied [56]. Plating time was varied from 30 to 160 seconds, frequency from 500-4000Hz, current density from 0.02 to 0.1 Adm$^2$ and $t_{on}/t_{off}$ ratio from 10 to 50. A rectangular pulse was used to coat zinc/nickel on AZ91 as shown in Fig.8. The coating thickness increased with increasing coating time and current density. However, it decreased with frequency increment and unchanged with increasing $t_{on}/t_{off}$ ratio. It was also noted that the particle size decreased higher frequency, larger current density and smaller $t_{on}/t_{off}$ ratio. This was attributed to the proportion of the nickel content deposited on the substrate [56].

5.1 Morphology of the coating and microhardness

AZ91 magnesium alloy was coated with Ni-SiC nano composites by pulse electrodeposition in an altered Watts bath. Square waveform with frequency 10 HZ, duty cycle 30% and current density 50mAcm$^{-2}$. Coating process was carried out for 150 minutes and a coating of 35 µm thickness was produced. The coatings were compact with no pores or cracks. Although some agglomerations were noticed, bath with 15 g/L of SiC yielded a more homogeneous microstructure as shown in Fig.9 [58].

Fig.9. SEM image of the coating deposited from the bath containing 15 g/L SiC

The microhardness of the Zn-Ni alloy coating increased with the coating time, current density, frequency and $t_{on}/t_{off}$ ratio. Pulse current resulted in grain refinement causing the microhardness to increase [56]. The influence of pulse plating parameters on the coating morphology and the effect of titania nano particles were studied. The coating with excellent coverage and maximum microhardness was obtained at an average current density of 4Adm$^2$. Twice as much as the volume of particles of TiO$_2$ deposited by direct current were deposited using pulse current at a low duty cycle and low frequencies helped in obtaining composite coatings in preferred orientation. The microhardness increased with increasing current density and then decrease due to high incorporation of nickel and reduced incorporation of reinforcement particles. Coatings with higher hardness were obtained at lower duty cycles due to high incorporation of titania particles effected by the longer OFF time [59]. The effect of pulse duration on the current efficiency during electrodeposition of copper revealed that the current efficiency decreased in the shortened pulses due to diffusion of atoms. However it increased in the microsecond range due to the direct incorporation of adatoms in the sites without dissolution of copper atoms [62]. Homogenous distribution of Alumina nano particles along the grain boundaries was observed. Due to the restricted movement of the grainboundaries, the microhardness increased with the inclusion of alumina [63]. GO (Graphene oxide) deposited with Nickel and tungsten exhibited an increase in the microhardness of the coating in proportion to the GO deposited. A maximum hardness of 725 Hv was achieved with 5 g/L of GO [64]. Self annealing phenomenon inducing nano twinning was observed in pulse
electroplated copper films. Preferred fiber textures through recrystallization was noticed. Electrodeposition of copper films was done with pulse current and direct current with the average current density of the pulse current for comparison. TEM images shown in Fig.10 reveal coherent twin boundaries in the copper films produced by pulse electrodeposition [65].

![Fig.10. Nanoscale twinning by TEM](image)

5.3 Wear resistance
Pulse plated Ni-SiC composite coatings with an adhesion strength of 11 MPa were produced on AZ91 magnesium alloy. The wear rate of the samples decreased with increasing SiC content in the bath as shown in Fig.11 and the hardness values increased in agreement. It is clearly understood by comparing the SEM images of uncoated and the coating containing 15 g/L of SiC as shown in Fig.12.

![Fig.11. Wear rate of the coatings with increasing SiC concentrations [58].](image)

![Fig.12. SEM images of worn surfaces with (a) No SiC and (b) 15 g/L of SiC](image)

The wear volume loss was found to decrease dramatically from 0.005mm³/m for the uncoated sample to 0.0006 mm³/m to the sample coated with 15 g/L of SiC [58]. Zinc was electroplated on AZ31 magnesium alloy using DC and PC. Coating with direct current resulted in thin porous zinc layer with coarser grains. However, smoother coating with fine grains and lower macro residual stress was produced using pulsed current. High current density used during the ON time in pulse current increases the rate of nucleation and OFF time slows the grain growth producing finer grains. Pulsed mode help release the residual stresses in the coating thus decreasing the pores. The effect of current density, duty cycle, high over potential was studied for direct and pulse current. The current efficiency decreased with increasing current density and vice versa. Short ON time coupled with high current density promoted nucleation resulting in finer grains. Uniform grains with compact and dense coating with less or no porosity were produced with pulse current [61]. Observation of the wear tracks of alumina embedded nickel matrix revealed adhesion wear had occurred. The coefficient of friction reduced due to the incorporation of alumina and also the macro residual stresses were less when compared to direct current coated films [80]. The coefficient of friction decreased with the increase in the amount of GO exhibiting less wear. Studying the worn surface morphology revealed that a combination of abrasive and adhesive wear had happened. The surface exhibited narrow abrasive grooves with less depth [64].

5.4 Corrosion
The poor corrosion resistance of the uncoated AZ91 was well understood from the corrosion current and potential values of 0.13 mAcm⁻² and -1.6 V. The corrosion current reduced to 1.74 mAcm⁻² and the corrosion potential increased towards -0.31V in the sample with 15 g/L of SiC. This is due to the fact that area of contact of substrate with the corrosion media is reduced when covered by hard SiC particles with excellent corrosion resistant properties. The change in the morphology from columnar structure to coaxial one after the addition of SiC particles inhibited the rate of corrosion [58]. Due to the higher nickel concentration along the grain boundaries as compared to grain centers, micro potential difference arose and gave rise to micro chemical reactions. The grain boundaries act as cathodes and grain interiors as anodes leading to corrosion as shown in Fig.13 (a) and (b) [56].
Fig. 13. (a) SEM (b) plot of variation from particle brim to center [56].

The uneven surface and the fine pits paved for way for corrosion in case of DC. However, pulse current provided complete coverage producing a homogeneous, compact and uniform grains of zinc. The results of corrosion tests shown in Fig. 14 are in accordance with the corrosion test results [60].

Fig. 14. Potentiodynamic polarization curves for bare AZ31 alloy, Zinc coated with DC and PC

The reaction of nickel alloy matrix with the bath solution was restricted by the addition of GO which formed a passive shielding layer on the matrix. The diffusion of corrosive ions in the matrix is also avoided by the adsorbed GO atoms improving the corrosion potential. Homogeneous distribution of GO particles reduced localized corrosion [64].

CONCLUSIONS

From this review we understand that electrocodeposition is an economical and effective technique to improve the coating properties such as microhardness, wear resistance and corrosion resistance. Magnesium being a highly reactive metal has to be subjected to special treatment procedures prior to coating. Zinc immersion coating or electroplating followed by copper undercoat is the most effective method to obtain a compact undercoat for subsequent nickel electrodeposition. Coating morphology and in turn the coating characteristics can be altered by the addition of hard phase reinforcements and careful control of process parameters such as current density, pH, temperature of the bath, percentage of reinforcements, etc. Conventional direct current is capable of producing durable coatings; however, compact and denser coatings with exceptional properties to suit the applications can be tailored only by pulse current. Various wave forms of pulse current such as rectangular, square, triangular, ramp up and ramp down are capable of producing functionally graded coatings. The effect of peak current density, duty cycle, frequency, etc. on the coating properties are well understood from the literatures discussed in this review. It is inferred that a very limited work has been done on the pulse electrodeposition of magnesium alloys. Therefore, the area of electrodeposition of magnesium alloys with various forms of pulse current could be explored further.

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