

# Influence of Pulse Frequency on Physical and Mechanical Properties of Ni-GO Composite Coating

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## ABSTRACT

Coating serves as an effective and reliable barrier that protects surfaces against wear and less friction. Among the various deposition techniques, the pulse electrodeposition method has gained significant attention owing to its capability to generate tailored fine-grained, dense and uniform coatings. The properties of these coatings are highly influenced by several process parameters. This work explored the influence of pulse frequency on the physical and mechanical properties of fabricated nickel-graphene oxide (Ni-GO) composite coatings. The coatings were deposited on carbon steel with GO platelets concentration of 0.05 g/L through a 45-minute deposition at a temperature of 45 °C by pulse electrodeposition method. The pulse current frequency was varied from 200 Hz to 500 Hz. Surface morphology, surface roughness, coating thickness, microhardness, and phase structures were examined using Scanning Electron Microscope, Alicona InfiniteFocus, Micro-Vickers Hardness Testing Machine, and X-ray Diffractometer respectively. The highest coating hardness of 245.4 HV was obtained at the highest pulse frequency of 500 Hz. Surface roughness was drastically reduced to 0.3 µm as the pulse frequency increased to 500 Hz. The thickness of coatings increased with increasing pulse frequency, from 17.2 µm to 27.1 µm before decreasing to the lowest thickness of 14.0 µm at 500 Hz. The XRD spectrum revealed that increasing pulse frequency resulted in the formation of a refined granular coating structure exhibiting a prominent orientation along the Ni (220) crystal plane. In conclusion, the physical and mechanical characterisations of the coatings are notably associated with pulse current frequencies used in deposition process.

## Introduction

Tribological coating is employed to protect surfaces that are prone to friction and wear due to interaction between solid surfaces (Li et al., 2021a; Okokpuije et al., 2024). A coating is a specialised thin layer of

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materials on surfaces acting as a barrier against mechanical and chemical degradation. These engineered layers improve the efficiency, performance, and lifespan of machinery and mechanical systems by minimizing adverse influences of surface contact, such as wear, energy loss, and excessive heat generation. In many cases, tribological coatings also enhance the corrosion performance of surfaces, serving as a protective barrier in highly corrosive environments (Wang et al., 2025; Zhu et al., 2023). Furthermore, coatings can be tailored to specific applications in various engineering sectors, including automotive, aerospace, marine, biomedical, and energy industries. Depending on the deposition method and material composition, tribological coatings can exhibit unique properties such as self-lubrication, improved friction-reducing performance, high hardness, the ability to withstand extreme temperatures etc. Recent advances in coating technologies, such as nanocomposite and multilayer structures, have further expanded their potential by enabling coatings with superior mechanical and tribological performances.

Composite coatings are advanced coatings that combine two or more constituents. Composite coatings reinforced with fillers or nanoparticles have been shown to significantly enhance tribological performance, offering lower friction coefficients and higher hardness than conventional coatings (Ma et al., 2024; Yang et al., 2023). Improvements of more than 70% reduction in friction and increase in wear resistance reported for several reported polymer composite and metal–matrix such as graphene-based composites highlight the superior durability of composites coatings (Ren et al., 2021; Ying et al., 2021; Shahin et al., 2021; Llorente et al., 2020; Da et al., 2020). These findings underline that composite coatings leverage collaborative effects between the matrix and reinforcement, enabling superior mechanical and tribological performance relative to conventional single-material coatings (Ren et al., 2021). The integration of nanoparticles in metal matrix composite coatings provides excellent functional properties, thereby improving tribological properties (Ren et al., 2021; Ying et al., 2021). Among metal matrix composite coatings, nickel (Ni)-based composite coatings are widely recognized for high hardness, excellent resistance to wear, and self-lubricating properties (Xiang et al., 2019).

Numerous techniques have been adopted for coating fabrication, such as cold spray, sol–gel processing, thermal spraying, physical vapor deposition (PVD), chemical vapor deposition (CVD), and electrodeposition (Pan et al., 2022; Guo et al., 2022; Latka et al., 2020; Huang et al., 2013). One of the most common and facile methods to deposit composite coating is by electrodeposition. Through this method, coating deposition can be achieved using several types of current, for example direct current (DC) and pulse current (PC). Pulse electrodeposition offers control over the chemical composition, crystallite size, and surface qualities of the coatings (Ji et al., 2018). In contrast, PC deposition process involves the application of current using a waveform with "on" and "off" durations, resulting in higher quality coatings compared to the DC approach with slower double-layer discharging and ion redistribution processes (Pramod Kumar et al., 2019).

The exceptional properties of graphene have made it one of the most extensively investigated nanomaterials in both scientific research and industrial applications. Graphene is a two-dimensional network of  $sp^2$ -bonded carbon atoms. Its applications range from fuel cells to biological devices and anti-corrosion coatings (Tabish et al., 2021). Studies have demonstrated the excellent anti-corrosion performance of graphene coatings and the minimal visible changes in graphene-coated metals under harsh conditions (Vinodhini & Xavier, 2021). Graphene possesses properties such as thinness, wear resistance with extraordinary mechanical properties (Karimzadeh et al., 2020). Graphene oxide (GO) and nanodiamond (ND) have also been reported to act as performance-enhancing additives in water lubricants (Kinoshita et al., 2014). Research in tribology aims to improve machinery efficiency, reduce breakdowns, enhance performance, and achieve cost savings. Wear protection and friction reduction coatings have garnered increasing interest in enhancing lubricity and extending lifespan in challenging tribological applications. Coatings, which involve depositing layers of material onto a substrate, aim to improve surface properties, and the composition of coatings results in a huge range of structures and properties (Huang et

al., 2020). Graphene, with its exceptional mechanical strength, elastic modulus, electrical conductivity, surface area, and anti-corrosion properties, is an excellent material for coating applications (Raghupathy et al., 2017).

Graphene additions in polymer-based coatings have led to dramatic reduction in coefficient of friction and about 76% reduction of wear rate at room and elevated temperatures, owing to graphene's self-lubricating transfer film and excellent mechanical support (Zhang et al., 2018). In ceramic-based systems, a small amount of graphene of approximately 0.025 wt.% embedded in titanium oxide (TiO<sub>2</sub>) films notably reduced friction by enhancing film surface smoothness and facilitating grain refinement (Wang et al., 2023). Similarly, Lei et al. (2018) has also previously reported that in metal matrix composites such as Ni, the introduction of graphene reduced coefficient of friction, thereby enhance the wear resistance.

Compared to other graphene derivatives, GO offers several advantages for coating in tribological applications. Unlike pristine graphene, graphene oxide contains a high density of oxygenated functional groups of hydroxyl (–OH), carbonyl (C=O), epoxy (–O–), and carboxyl (–COOH), on its basal planes and edges. The existence of these functional groups enables uniform dispersion in aqueous and polar solvents prior to coating, thereby promotes homogeneous nucleation during coating deposition (Wakchaure & Menezes, 2025). This promotes the formation of more stable tribofilms, improving load transfer efficiency, hence promoting superior tribological properties of the coating (Jiang et al., 2025). The characteristics make GO highly suitable reinforcing material for electrodeposited composite coatings (Wakchaure & Menezes, 2025; Li et al., 2021b; Nemati et al., 2016). Kinoshita et al. (2014) has previously reported that the two-dimensional layered structure of GO facilitates easy interlayer shear, thereby reducing friction during sliding. Moreover, Nemati et al. (2016) also reported that the well-dispersed GO network can hinder crack propagation and contribute to thermal stability by dissipating frictional heat.

Ni-based graphene derivatives composite coatings have attracted considerable attention due to their unique and excellent mechanical and tribological properties. Although pulse electrodeposition has been demonstrated to produce finer and denser coatings, the specific role of pulse frequency in controlling the Ni and GO deposition remains poorly understood. This study investigates the influence of pulse current frequency (200 Hz to 500 Hz) on the deposition of nickel-graphene oxide (Ni-GO) composite coating deposited via pulse electrodeposition method. The physical and mechanical properties of the Ni-GO composite coating were studied. The main contribution of this study is establishing the correlation between processing conditions, microstructure, and coating performance through systematic variation of pulse frequency. It provides insights into the optimisation of electrodeposition parameters for achieving desirable coating characteristics. The findings of this work will contribute to the clearer understanding of the deposition mechanism governing coating characterisations.

## Experimental Procedure

A rectangular ASTM A36 steel substrate was used, measuring approximately 66 mm x 32 mm x 4 mm, with tapered edges. This size adhered to the requirements of the pin-on-disc wear testing machine for subsequent investigations. Prior to the deposition process, the substrates were sequentially ground and polished with emery papers 180, 240, 320, 600, and 1200 until a smooth, uniform, and reflective surface was obtained. Following this, the substrates were degreased in acetone, immersed in ethanol, and subjected to a 10-minute ultrasonic bath treatment to eliminate surface impurities, rust, oil, and dust. To measure the coating thickness during the electrodeposition process, a 32 mm x 5 mm piece of Kapton tape was applied across the polished surface of each substrate.

To prepare the electrolyte or aqueous bath, a chemical powder mixture of nickel sulphate ( $\text{NiSO}_4$ ), GO, boric acid ( $\text{H}_3\text{BO}_3$ ), saccharin powder and ascorbic acid were dissolved in 1 liter of deionised (DI) water. The electrolyte pH was fixed at 3 throughout the deposition process. Once all the chemicals had been fully dissolved in the DI water, the electrolyte was heated to a temperature of 45 °C. Table 1 provides the bath composition of the electrolyte used in this work. The pulse electrodeposition system consisted of a function generator and an oscilloscope. The positive output of the power supply was connected to the graphite anode, while the negative terminal was connected to the mild steel cathode. Both electrodes were submerged in the electrolyte bath, with the electrolyte temperature maintained at 45 °C and stirred at 300 rpm. Fig. 1 illustrates the experimental setup using the pulse electrodeposition method. The pulse electrodeposition process was fixed at duty cycle of 60% and the pulse frequency was varied at 200 Hz, 300 Hz, 400 Hz and 500 Hz. The pulse period,  $T$ , was determined from the pulse frequency,  $f$ , according to Equation 1:

$$T = \frac{1}{f} \quad (1)$$

where  $T$  is the pulse period (s) and  $f$  is the pulse frequency (Hz). Since duty cycle,  $D$  was maintained at 60% throughout the deposition and is defined as in Equation 2.

$$D = \frac{\text{Pulse} - \text{On}}{T} \times 100\% \quad (2)$$

Table 1. Bath composition for electrolyte

| Bath Composition                                                                               |           |
|------------------------------------------------------------------------------------------------|-----------|
| Nickel sulphate hexahydrate ( $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ , ≥99%, Sigma-Aldrich) | 35.04 g/L |
| GO (particle size ~1–5 μm, Graphenea)                                                          | 0.05 g/L  |
| Boric acid ( $\text{H}_3\text{BO}_3$ , ≥99.5%, Merck)                                          | 16.48 g/L |
| Ascorbic Acid                                                                                  | 11.74 g/L |
| Saccharin Powder                                                                               | 1.36 g/L  |

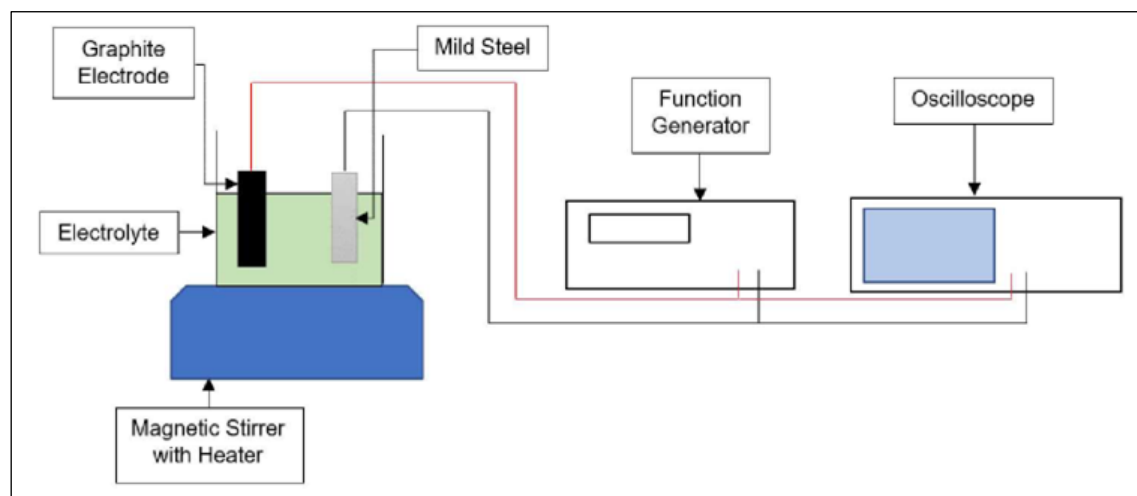


Fig. 1. Schematic of the pulse electrodeposition process.

Table 2 tabulates the pulse electrodeposition parameters of the Ni-GO composite coatings. The deposition temperature, time, pH and agitation rate were maintained at 45 °C, 45 minutes,  $3.0 \pm 0.3$  and 300 rpm respectively. Each experimental condition was repeated three (3) times to ensure the repeatability and reliability of the results. The substrate was fully immersed in the electrolyte, with an electrode-to-electrode distance of approximately 80 mm.

Table 2. Pulse electrodeposition parameters

| Pulse Electrodeposition Parameter |                 |
|-----------------------------------|-----------------|
| Duty Cycle                        | 60%             |
| Pulse Frequency (Hz)              | 200,300,400,500 |
| Temperature                       | 45 °C           |
| Time                              | 45 minutes      |
| pH                                | $3.0 \pm 0.3$   |
| Agitation rate                    | 300 rpm         |

Surface morphology and cross-sectional microstructure of the deposited coatings were examined using a Scanning Electron Microscope (SEM) equipped with an Oxford Instruments energy-dispersive X-ray spectroscopy (EDX) detector. Prior to observation, the coated specimens were cleaned with ethanol and dried under ambient conditions. SEM imaging was performed to evaluate the surface morphology and coating integrity, while EDX analysis was conducted to determine the elemental composition of the deposited coatings. X-ray diffraction (XRD) was used to investigate crystallographic features and chemical composition. Surface roughness measurements were carried out using an Alicona InfiniteFocus. The Vickers Microhardness Tester was utilised to evaluate the surface microhardness of the coatings (ASTM E92) under an applied load of 1 kgf (HV1), with dwell time of 15 seconds. For each specimen, three (3) indentations were made at different locations on the coating surface, and the reported hardness values represent the mean of these measurements.

## Results and Discussion

The surface characteristics of Ni-GO composite coatings were examined by SEM, and the corresponding micrographs are presented in Fig. 2(a – d). The magnification used for the sample was x500. The micrographs reveal relatively rough surfaces of Ni-GO coatings deposited using pulse frequency of 200 and 300 Hz (Fig. 2(a) and (b)). Some spherical particles can be spotted in all the figures which represent Ni (marked with the red arrows). Non-uniform deposition of coatings can also be observed in Fig. 2(c) and (d) which represent the surface morphology of coatings deposited at frequency of 400 and 500 Hz. Nguyen-Tri has previously reported that the increase in deposition pulse frequency produced a non-uniform coating due to insufficient attachment to the surface of the substrate (Nguyen-Tri et al., 2018).

Energy-dispersive X-ray spectroscopy (EDX) was used to investigate the relative amount of elements for the deposited coatings. The results are presented in Table 3. High iron (Fe) content and part of carbon (C) elements may originate from the underlying substrate of steel rather than the coating itself. The measured Ni element is largely similar across all coatings with atomic percentage of between 0.2 to 0.4%. No oxygen (O) element was detected in the EDX spectra. There are several factors that may contribute to this finding. First, the GO concentration used in this work was relatively low. Consequently, the O content associated with oxygen-containing functional groups of GO may be too low to be detected by the conventional SEM-EDX analysis. Another reason is the strong Ni signal may have dominated the EDX spectrum and mask the weak signals from light elements such as O. In addition, O is a low atomic number element, for which EDX generally exhibits lower detection sensitivity and poorer quantitative accuracy

especially when present within a dense metallic material (Guyett et al., 2024). Similar observations have also been reported for Ni-GO and related metal-graphene derivatives composite coatings, where GO-related signals were either weak or undetectable due to low graphene content and dominant diffraction signals from the metal matrix (Khorasani & Sanjabi, 2016).

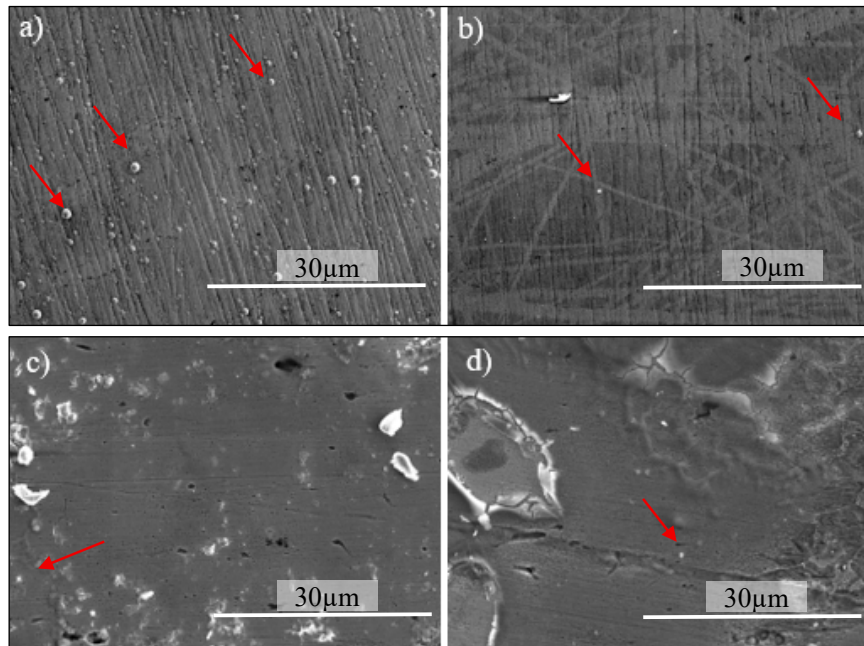


Fig. 2. SEM micrographs of the Ni-GO composite coatings fabricated at pulse frequencies of (a) 200 Hz, (b) 300 Hz, (c) 400 Hz, and (d) 500 Hz.

Table 3. EDX percentage of elements

| Pulse Frequency (Hz) | Element (at. %) |     |      |
|----------------------|-----------------|-----|------|
|                      | Fe              | Ni  | C    |
| 200                  | 81.3            | 0.4 | 18.3 |
| 300                  | 92.4            | 0.2 | 7.4  |
| 400                  | 80.2            | 0.3 | 19.5 |
| 500                  | 93.7            | 0.2 | 6.1  |

Fig. 3 exhibits the surface roughness of the Ni-GO composite coatings, respectively. The microhardness exhibited an increasing trend while roughness generally decreased with pulse frequency. The highest surface roughness is observed at lowest pulse frequency of 200 Hz, while the finest surface roughness is observed at 500 Hz. The coating deposited at 200 Hz exhibited the highest roughness, with an average  $R_a$  value of approximately 1.28  $\mu\text{m}$ . Increasing the frequency to 300 Hz reduced the roughness to about 0.95  $\mu\text{m}$ , followed by a slight decrease to around 0.84  $\mu\text{m}$  at 400 Hz. The lowest roughness, approximately 0.34  $\mu\text{m}$ , was obtained at 500 Hz, indicating that the coating surface became considerably smoother at the highest pulse frequency investigated. The reduction in surface roughness at higher pulse frequencies is attributed to the shorter pulse-on time, which increases the nucleation rate while limiting excessive growth. As a result, the coating develops a finer and more compact microstructure, leading to a smoother surface finish.

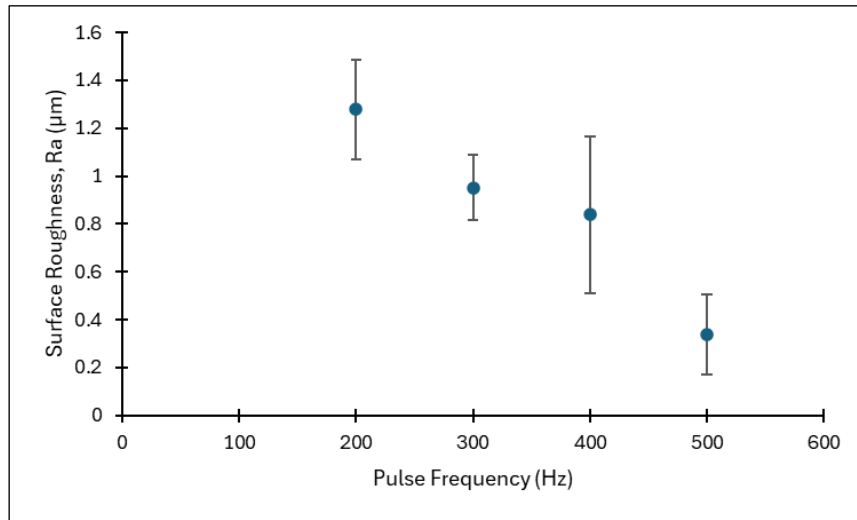


Fig. 3. Surface roughness of Ni-GO composite coatings fabricated at pulse frequency of 200, 300, 400 and 500 Hz.

Fig. 4 shows the variation in the microhardness of the Ni-GO composite coatings fabricated at different pulse frequencies. The hardness increased noticeably when the pulse frequency was raised from 200 to 300 Hz. The coating deposited at 200 Hz recorded the lowest hardness, approximately 196 HV. Increasing the frequency to 300 Hz resulted in a substantial increase to around 245 HV. At 400 Hz, the hardness decreased slightly to about 241 HV; however, the difference was relatively small and within the range indicated by the error bars. The highest hardness, approximately 246 HV, was obtained at 500 Hz, suggesting that higher pulse frequencies generally promote the formation of harder Ni-GO composite coatings. The shorter pulse-off time at 500 Hz pulse frequency hinders particle growth thereby improving particle distribution on the substrate and surface roughness (Xia et al., 2014). In addition, at this high pulse frequency, much larger amounts of nucleation with finer grains were produced, which increased the hardness. This is consistent with many previously reported works on Ni-based composite coatings (Xia et al., 2014; Hu & Chan, 2006).

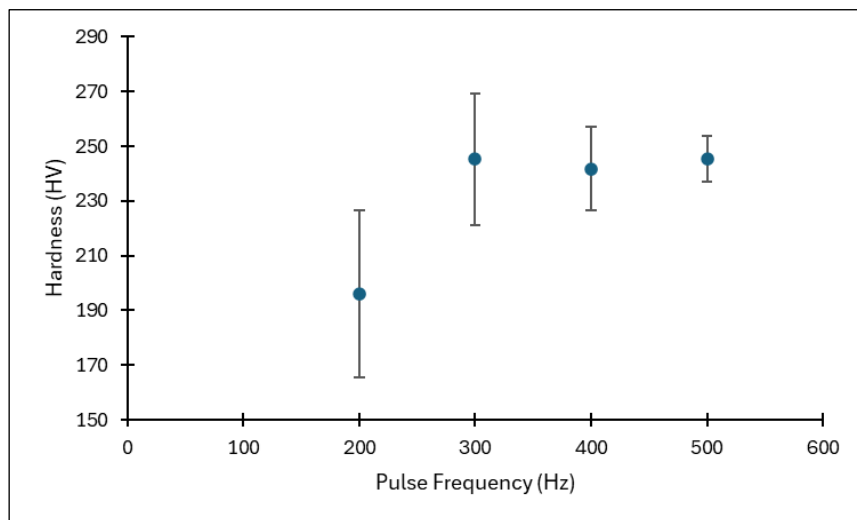


Fig. 4. Hardness of Ni-GO composite coatings deposited at frequency of 200, 300, 400 and 500 Hz.

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Fig. 5 shows comparative XRD spectra of Ni-GO composite coating at pulse frequencies from 200 Hz to 500 Hz during deposition. The XRD patterns reveal highly oriented crystals with distinct peaks in the composite coatings. Within these coatings, peaks were observed at  $2\theta$  values of  $44^\circ$  and  $65^\circ$ , corresponding to face-centred cubic (FCC) of Ni. The dominant peak at  $2\theta \approx 44^\circ$  belongs to Ni (200) plane, while the other peak at  $2\theta \approx 65^\circ$  is indexed to the Ni (220), consistent to the JSPDS No. 04-0850. These peaks provide evidence of the crystallographic characteristics of the Ni matrix despite the incorporation of GO. The increase of the peak intensity from 200 to 500 Hz indicates an enhancement in the crystallinity of Ni along the (200) plane. This suggests that higher pulse frequency promotes rapid nucleation of Ni during electrodeposition thus resulting in higher crystallinity. This finding is supported by the results of coatings hardness discussed earlier that the hardness increased with pulse frequency. Despite the change in the intensity, the full width of half maximum (FWHM) of the dominant Ni (200) are also similar across all pulse frequencies. This indicates that crystallite size of Ni in all coatings does not vary significantly with pulse frequency. No distinct GO diffraction peak was observed in all the spectra. Diffraction peak for GO is commonly expected at around  $2\theta \approx 10\text{--}12^\circ$  (Raghupathy et al., 2017; Marcano et al., 2010). Similarly to what has been discussed earlier for EDX observation, the absence of the peak can be attributed to the fact that the concentration of GO used in this work is relatively low (0.05 g/L) which may be below the detection limit of XRD signal. This may also reveal that the GO nanoplatelets are likely to be dispersed and embedded within the Ni matrix, leading to the disruption of their layered stacking structure that gives rise to the characteristic of GO peak. Zhang et al. (2019) reported similar findings where there was no XRD diffraction peak corresponding to GO was observed in Ni-W-GO composite coatings. The observation is also consistent with several previous reports on electrodeposited Ni and GO-related composite coatings, where the GO content cannot be detected in XRD spectra (Tseluikin et al., 2023; Zhang et al., 2022; Qi et al., 2017).

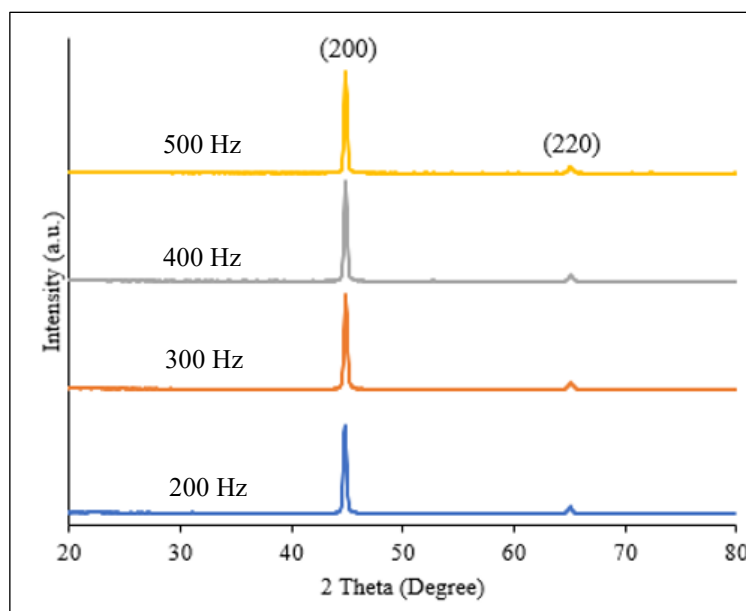


Fig. 5. XRD spectra of the Ni-GO composite coatings deposited at frequency of 200, 300, 400 and 500 Hz.

Fig. 6(a - d) presents representative SEM cross-sectional micrographs of the Ni–GO composite coatings deposited under different pulse frequencies of 200 Hz to 500 Hz. The yellow lines indicate the coating thickness, while the regions above and below correspond to the coating and mild steel substrate, respectively. The cross-sectional observations were performed to investigate thickness, morphology and integrity of the Ni–GO composite coatings. Distinct coating layers can be observed on the mild steel substrate under all deposition conditions confirming successful coating formation. However, the coating morphology and thickness varied noticeably with pulse frequency. At 200 Hz pulse frequency, a relatively thin and continuous coating layer is observed. Almost no surface irregularities can be observed indicating good coating growth during position. The results revealed that thickness of the coating decreased as the pulse frequencies increased. At 300 Hz the coating appears thicker and more compact. This may indicate more formation of nuclei and deposition during deposition as compared to deposition at 200 Hz. As the pulse frequency increased to 400 Hz, the coating quality deteriorated noticeably. At 500 Hz pulse frequency, the coating exhibits obvious uneven thickness and visible defects. At high pulse frequency, nucleation rate and crystallographic improved, but due to more frequent disruption of nucleation, growth and deposition, coating was not properly formed. Although the coating deposited at 500 Hz exhibited the lowest surface roughness as presented in Fig. 3, this does not contradict the observed reduction in coating thickness. Surface roughness characterises the surface topography, whereas coating thickness reflects the overall deposition rate and coating growth. The smoother surface observed at 500 Hz is attributed to grain refinement rather than increased coating thickness.

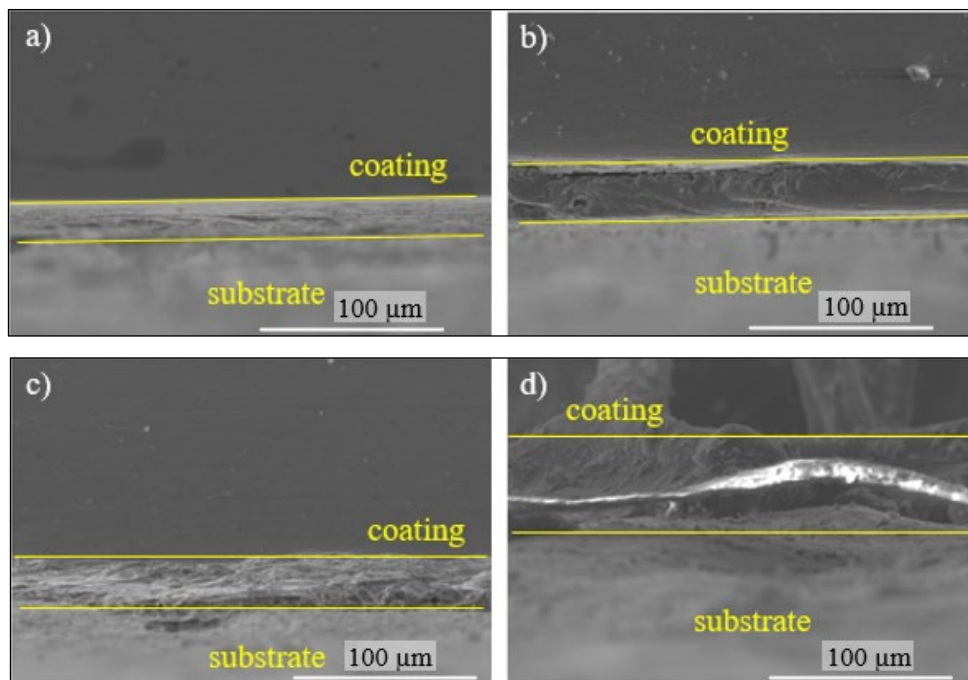


Fig. 6. Comparative cross-sectional micrographs of Ni–GO composite coatings at varied pulse frequencies of a) 200 Hz, b) 300 Hz, c) 400 Hz, and d) 500 Hz.

Fig. 7 illustrates the influence of pulse frequency on the average thickness of the Ni–GO composite coatings. The thickness was measured based on the cross-section observation captured in Fig. 6. The coating thickness increased from approximately 17.2  $\mu\text{m}$  at 200 Hz to a maximum of 27.1  $\mu\text{m}$  at 300 Hz. Beyond this frequency, the coating thickness decreased to about 21.0  $\mu\text{m}$  at 400 Hz and further declined to approximately 14.0  $\mu\text{m}$  at 500 Hz. These results show that the coating thickness initially increased with pulse frequency, reaching an optimum value at 300 Hz, before decreasing at higher frequencies. The small error bars indicate that the thickness measurements were relatively consistent across all deposition conditions but slightly bigger for the coating deposited at 500 Hz. Higher error bar for coating deposited at 500 Hz revealed the non-uniform thickness formation compared to the other lower pulse frequency.

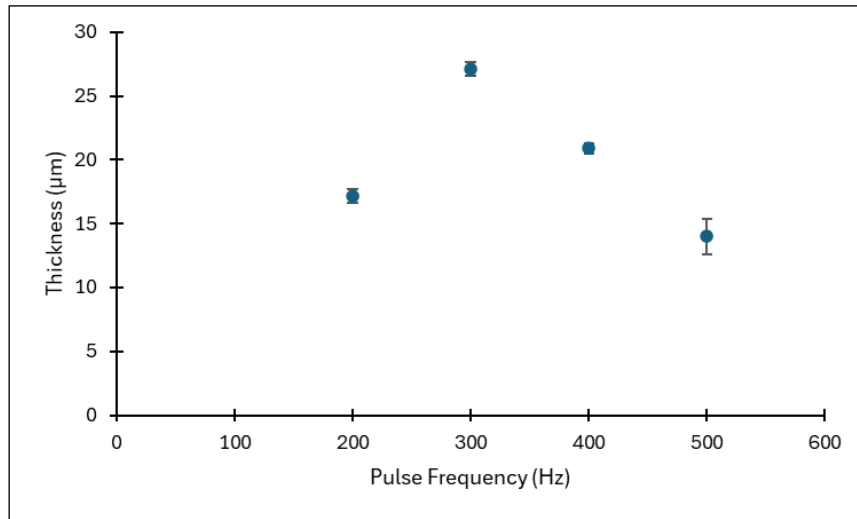


Fig. 7. Thickness of Ni-GO composite coatings as a function of pulse frequency.

In theory increasing pulse frequency indicates shorter duration of pulse-on and pulse-off (Equation 1 and 2). During pulse-on nucleation happens and the existing nuclei continue to grow by atom deposition. Deposition occurs during this time. At the same time, electrophoretic forces during pulse-on drive GO to the surface (Joseph et al., 2021). On the other hand, during pulse-off, no Ni deposition takes place because the current is off. Fig. 8 illustrates possible formation of nucleation and growth of  $\text{Ni}^{2+}$  ions during each pulse frequency. Coating thickness increased up to 300 Hz due to longer pulse-on duration that gives opportunity for more nucleation and crystal growth, resulting in an increase in coating thickness. At higher frequency however, the pulse-on time becomes considerably shorter, limiting the crystal growth during each pulse. At higher pulse frequency, there are frequent more interruptions of deposition process which may have reduced the effectiveness of crystallite growth despite the higher nucleation rate.

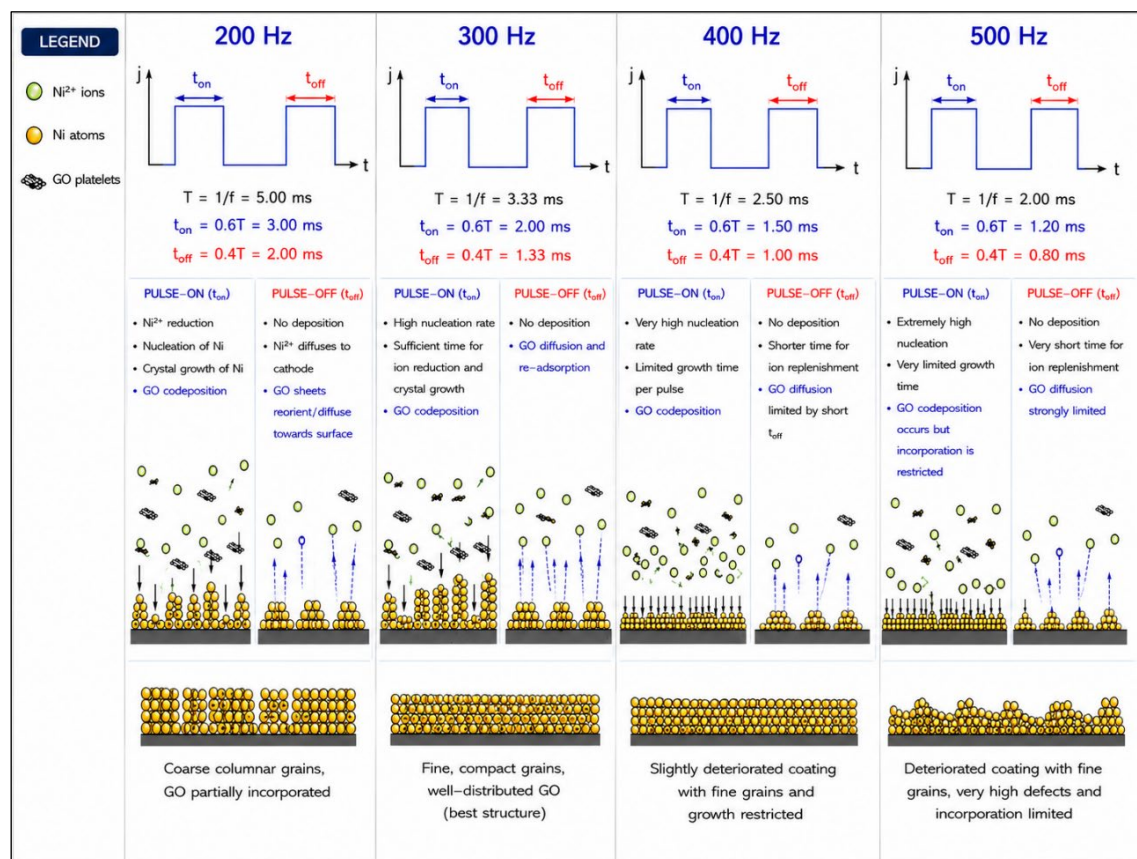


Fig. 8. Proposed nucleation and growth of Ni-GO composite coating with the change of pulse frequency of 200 to 500 Hz.

## Conclusion

Ni-GO composite coatings have successfully been fabricated using pulse electrodeposition at frequencies from 200 Hz to 500 Hz. The results demonstrate that pulse frequency is a critical electrodeposition parameter governing the surface morphology, surface roughness, microhardness, and thickness of the deposited coatings. The Ni-GO composite coating deposited at 200 Hz exhibited the highest surface roughness, with an average  $R_a$  of 1.28  $\mu\text{m}$ . As the pulse frequency increased, the roughness decreased progressively and reached the lowest value of 0.34  $\mu\text{m}$  at 500 Hz. The average coating thickness of the Ni-GO composites increased from 17.2  $\mu\text{m}$  at 200 Hz to a maximum of 27.1  $\mu\text{m}$  at 300 Hz. Further increases in pulse frequency reduced the coating thickness to 14.0  $\mu\text{m}$  at 500 Hz. XRD pattern analysis reveals that the Ni matrix in the coating enhances the preferred orientation along the (200) plane with improved crystallinity of the deposited Ni matrix. The highest microhardness of approximately 246 HV was achieved at 500 Hz, compared with 196 HV at 200 Hz, confirming that higher pulse frequencies enhanced the hardness of the Ni-GO composite coatings.

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## Conflict of Interest Statement

The authors agree that this research was conducted in the absence of any self-benefit, commercial, or financial conflicts, and declare the absence of any conflicts of interest with the funders.

## Authors' Contributions

The authors confirm their contribution to the paper as follows: study conception and design: Nik Roselina Nik Roseley, Nor Hayati Saad; experimental work and data collection: Noor Syahadah Yussoff; analysis and interpretation of results: Nik Roselina Nik Roseley, Noor Syahadah Yussoff, Cheng Seong Khe, Mohamad Ali Ahmad.; manuscript preparation and drafting: Nik Roselina Nik Roseley, Noor Syahadah Yussoff; critical review, supervision, and manuscript editing: Nor Hayati Saad, Cheng Seong Khe, Mohamad Ali Ahmad. All authors reviewed the results and approved the final version of the manuscript.

## Declaration of Generative AI in the Writing Process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist in the visualisation of the schematic of the explanatory images. The scientific concept, interpretation, and content of the proposed mechanism were developed by the authors. The AI-assisted illustration was revised and refined by the authors to ensure its scientific accuracy and consistency with the experimental findings. The authors take full responsibility for the content of the manuscript.

## Data Availability/ Supplementary Materials

The data generated and analysed during the current study are available from the corresponding author upon reasonable request.

## Ethics Statement

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA.

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