Compositionally modulated Ni-W multilayers to alleviate the residual stresses in coatings for superior wear resistance

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Abstract

The presence of tensile residual stresses in the Ni-W alloy coatings generated during the electrodeposition has restricted their industrial deployment. In the present study, the multilayering strategy is employed in developing the Ni-W coatings with the best combination of hardness and residual stresses. Ni-W multilayer coatings composed of alternate soft (~ 2.6 GPa) and hard (~ 8.5 GPa) Ni-W layers with individual layer thickness (λ) ranging from 2.5 μm to 0.05 μm were deposited by using the pulse reverse current electrodeposition. These multilayer coatings have demonstrated a significant reduction in the residual stresses while retaining the high hardness. Ni-W multilayer coating with λ ~0.1 μm has exhibited superior resistance to wear damage compared to its homogeneous counterparts. The improved wear degradation resistance of the multilayer coating was rationalized through assessment of residual stresses and thermal properties.

Keywords: *Pulse reverse electrodeposition; Ni-W alloy; Multilayer coatings; Microstructure; Wear.*

1. Introduction

For the past three decades, multilayers have been studied for wide variety of applications [1]–[4] after the pioneering theoretical framework proposed by Koehler [5] that paved the way for studying the mechanical aspects of multilayers. Techniques such as sputtering, vapor deposition and electrodeposition are extensively utilized to synthesize a wide range of multilayers. Early stages of metallic multilayer developments had majorly utilized the dual bath electrodeposition [6]–[10]. Later, with the advancement of microelectronics, sophisticated pulse power rectifiers were developed and enabled to control the pulses with narrow widths (as low as few microseconds) [11], [12]. This has revolutionized the electroplating industry and the fundamental research on metallic multilayers. The pulse electrodeposition process has facilitated the deposition of discrete layers with varying modulus, composition, grain size, microstructure etc., [13], [14].

The potential of the electrodeposited nanocrystalline Ni-W coatings to replace the hard chrome coatings has been widely recognized [15]–[18]. However, these nanocrystalline Ni-W coatings suffer from two major setbacks: (i) presence of tensile residual stresses [19] and (ii) inherent low toughness associated with the nanocrystalline microstructure [20]–[22], which limited their wide industrial applications. The tribological performance of coatings is heavily influenced by both the properties mentioned above. Hence, for superior tribological performance, ensuring improved toughness along with high hardness/strength is vital. In pursuit of establishing the strength-ductility synergy in nanocrystalline materials, recent studies have elaborated the paradigm of microstructural engineering [23]–[25]. In brief, it is noticed that the deliberate inclusion of spatial gradients in microstructure and/or mechanical properties at various length scales has enabled the nanocrystalline metals to regain an appreciable amount of balance between the strength and ductility. A similar microstructural engineering strategy can also facilitate in reducing the tensile residual stresses often encountered in electrodeposited alloy coatings [26], [27].

Recent studies involving the electrodeposition of metallic multilayers for tribological applications have tried to address some of the above-mentioned issues and succeeded to an extent. Extensive studies conducted by Ruff and Lashmore [28] have concluded that the Cu/Ni multilayers (layer thickness, λ ~4 to 100 nm) have superior wear resistance compared to their homogeneous counterparts. The high wear resistance of multilayers is attributed to the interfacial barrier effects and the increase in the flow strength. Ghosh et al. [29] have investigated the effect of Ni layer thickness while keeping that of Cu layer constant, on the wear resistance of Cu/Ni alloys. They observed that layering has reduced the residual stresses with a concurrent increase in the hardness leading to improved wear properties. Similar observation was found in Ni-P [30]. Karimazadeh et al. [31] have used the pulse reverse current method to deposit the compositional modulated Ni-Co-P multilayers (λ ~90 to 3000 nm). The hardness of multilayers has shown a Hall-Petch type of relationship with layer thickness. The high wear resistance of multilayers is attributed to the enhanced hardness. Papachristos et al. [32] have reported that the brittle failure of Ni-P-W multilayer coatings under sliding is inhibited as the layer thickness is reduced, and it was attributed to the increased number of interfaces which may deflect the growing crack. However, explicit evidences for the crack deflection at the layer interfaces are not available. A similar wear behavior is also observed in the other multilayer systems [33]–[36].

The perusal of the literature suggests two important design guidelines: (a) sandwiching the hard layers between the soft layers to alleviate the residual stresses in addition to improve the toughness, and (b) layer thickness of few nanometers for increasing hardness. Despite the efforts, the multilayer systems mentioned above are still inferior to the existing hard chrome coatings in terms of their hardness and wear resistance. There is limited work carried out in this direction to develop wear resistant Ni-W multilayer coatings [16], [35-37]. Furthermore, there is lack of understanding on the effect of layering on the improved tribological properties especially in case of the multilayers which do not satisfy the Koehler's criteria i.e., the multilayers constituting of layers with marginal difference in the modulus. Therefore, the focus of the current study is to develop a method for depositing Ni-W multilayers consisting of alternate hard and soft Ni-W layers from single bath and subsequently, to understand the origin of the improved mechanical, tribological performance. The effect of thermal diffusion during wear has been emphasized.

2. Experimental

2.1 Controlling the W-content and microstructure

The advantage with the electrodeposited Ni-W system is that the W is a "weak grain boundary segregating" element unlike phosphorus in Ni-P system and widens the window of accessible grain size range [38-40]. Therefore, in the present study, pulse reverse current electrodeposition technique has been utilized to access the extreme grain size regimes and deposit soft and hard Ni-W layers from single bath consisting of citrate based electrolyte. The pulse parameters (such as anodic/cathodic current density and duty cycle) were optimized to obtain the homogeneous Ni-W coatings with extreme W-contents and grain sizes. The details on pulse parameters and deposition conditions are given in Table 1. Exploiting the recipe feature of the DPR 20-60-200 module, the Ni-W multilayers with equal layer thickness (λ) were deposited by alternating the deposition parameters. The individual layer thickness was controlled by passing equal amount of charge during each recipe. AISI 1045 steel plate (60 × 60 × 5 mm^3) is used as the substrate (cathode) material while the platinized titanium is employed as anode. The substrates were polished, cleaned in acetone and activated in a 50% HCl solution before introducing into the deposition bath. A fresh electrolytic bath of 2 L volume is used for every coating. After the deposition, the coated samples were cleaned in fresh water and dried. The deposition duration was tuned such that all the coatings have at least 30-40 μm thickness.

2.2 Coating characterization

Residual stresses were computed using the $Sin^2\Psi$ method by XRD technique (PANalytical X'Pert pro, 40 kV, 45 mA). The (2 2 0) plane (at 2θ = 75˚) was selected for the residual stress analysis.

The diffraction profile of this peak was collected at different Ψ-angles (± 71.57˚ with a step size of ~8˚) by tilting the sample stage. The obtained XRD profile data was corrected for the instrument-specific effects. Then, the peak position of each profile was determined and was used for the *d*-spacing calculations using the Bragg's law. The computed *d*-spacing values were plotted as a function of $Sin^2\Psi$. The procedure outlined in [41], [42] has been used to calculate the residual stress values. The elastic modulus values of the Ni-W alloys required for the calculations were taken from [43]. The thermal conductivity of coatings was estimated using electrical resistivity measurements. To measure the electrical resistivity of the coatings, free standing foils with ~30 μm thickness were prepared by depositing on copper substrate and later dissolving the substrate in a chromic acid solution (250 g/l chromium oxide and 15 ml/l sulfuric acid). The free-standing foils were carefully sectioned into 15×15 mm^2 samples for resistivity measurements. Four-probe instrument was used and at least three readings were taken at different regions of the film to arrive at an average resistivity value.

Table 1. Pulse parameters utilized for the deposition of compositionally modulated Ni-W layers

Parameter	Ni-1W layer	Ni-15W layer
Cathodic current density, A/cm^2	0.1	0.1
Anodic current density, A/cm^2	0.3	0
Duty cycle, %	87	97.5
Frequency, Hz	43	48.7
Temperature, °C	60 ± 3	

2.3 Sliding wear performance

Wear resistance of the coatings was evaluated using the ball-on-disc configuration with a universal tribometer (MFT-5000, Rtec instruments, USA) in accordance with the ASTM-G99 standard. The coated substrates were cut into 10×10×5 mm^3 specimens for wear tests. All the specimens were polished to a roughness (R_a) value <0.05 μm and cleaned in acetone before carrying out the test. Tungsten carbide (WC) ball having 6 mm diameter was used as the counter body. A fresh ball was employed for each test in order to avoid the debris transfer from one specimen to another. A constant normal load of 5 N at a sliding speed of 0.15 m/s was applied and the track diameter was set to 6 mm. The total sliding distance for each test was fixed to 200 m. Friction coefficient was continuously recorded. The specimens were ultrasonically cleaned to remove any loose particles on the wear track. Using an integrated profilometer, three-dimensional wear track profiles were recorded at different locations to estimate the wear volume loss as suggested in [15]. At least three tests were carried out and the average wear rate is reported. The SEM analysis of the wear tracks was carried out to understand wear mechanism.

3. Results and discussion

3.1 Microstructure

The cross-sectional SEM images in backscattered electron (BSE) mode for the Ni-W multilayers with varying layer thickness are shown in Fig. 1. The gray layers are Ni-1W while the bright layers are Ni-15W. The sharp interfaces between the individual layers as can be observed are intact and devoid of any cracks or pores. The waviness of the individual layers is attributed to the application of high anodic pulses during the deposition of Ni-1W layers. In fact, presence of such wavy interlayer interfaces could be advantageous, and the exact reasons will be discussed later while dealing with the residual stresses in the following sections. The elemental mapping reveals the compositional modulation of W-content between the layers.

3.2 Effect of multilayered architecture on the residual stresses

Fig. 2 shows the residual stresses computed using the $Sin^2\Psi$ method. All the coatings have shown tensile residual stresses. The homogeneous Ni-1W coating has shown the lowest stress of ~200 MPa which is much smaller than the earlier reports [19] while the Ni-15W coating has exhibited stress of ~1300 MPa, almost 7-fold higher than the former. In case of the multilayer coatings, irrespective of the layer thickness, residual stresses have significantly decreased compared to the homogeneous hard Ni-15W coating. The soft Ni-1W layers sandwiched between the hard Ni-15W layers could have

alleviated the residual stresses in the multilayer coatings. Furthermore, the presence of concave and convex type of topographic features on the Ni-1W layers can locally allow effective stress reduction and redistribution [44].

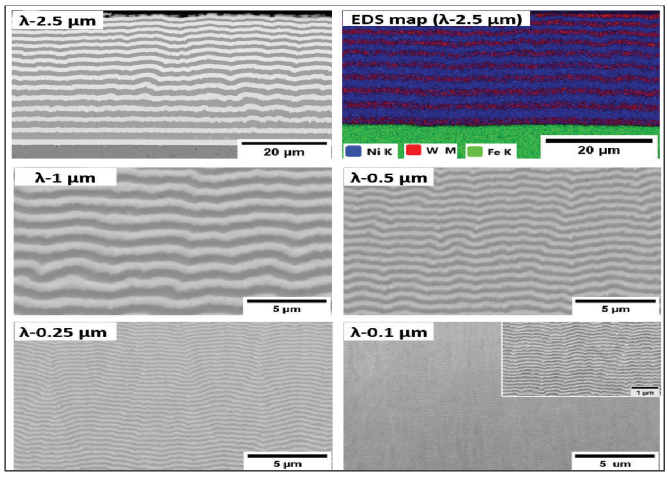


Fig.1 Cross-sectional images of Ni-W multilayer coatings with layer thickness (λ) ranging from 2.5 μm to 0.1 μm. EDS elemental mapping is shown for the Ni-W multilayer coating having λ ~2.5 μm to elaborate the compositional modulation between the layers.

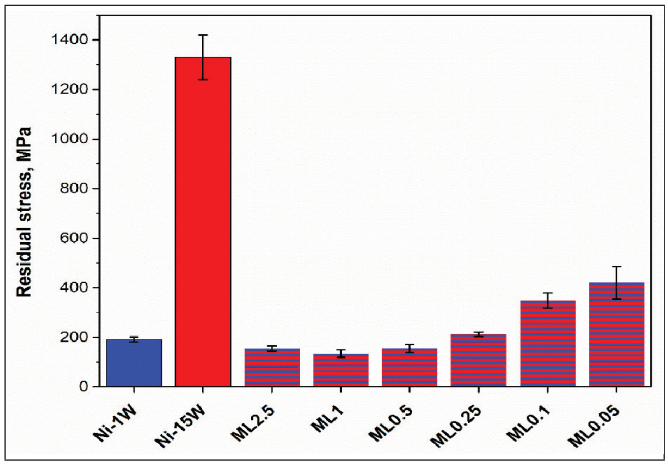


Fig.2. Residual stresses of the Ni-W homogeneous coatings (Ni-1W and Ni-15W) and multilayer coatings. ML represents multilayer while the number after ML indicates the layer thickness in micrometers.

3.3 Hardness and tribological behavior of multilayer coatings

The hardness of multilayer coatings is plotted against the layer thickness as shown in Fig. 3. Hardness increased with decrease in the layer thickness demonstrating the Hall-Petch type of behavior. An important observation from Fig. 3 is that the peak hardness of the multilayer coatings (which is obtained at λ ~0.1 μm) is only marginally higher than the hardness of homogeneous Ni-15W coating. This can be rationalized based on the Koehler's theory. Koehler proposed that the extent of multilayer strengthening is directly proportional to the difference in the elastic modulus of individual layers [5]. Since both the constituent layers (Ni-1W and Ni-15W) in the present study are solid solutions of W in Ni, the modulus difference is not large enough to produce extra strengthening.

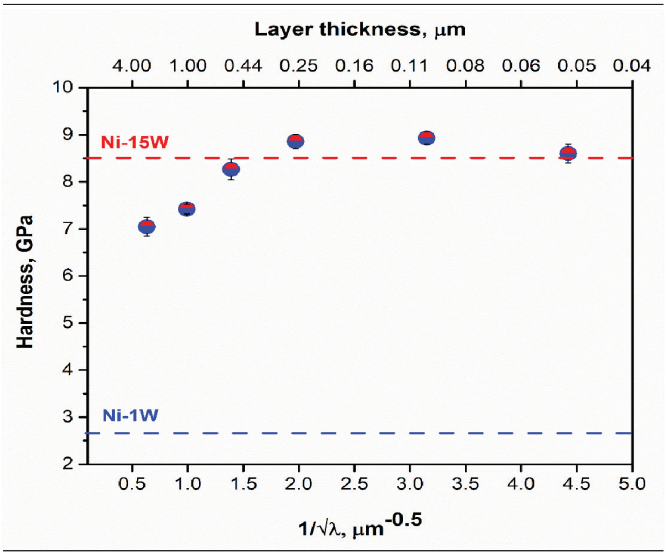


Fig.3. Hall-Petch type plot of Ni-W multilayer coatings

Tribological performance of the multilayer coatings were evaluated using the ball-on-disc configuration. Fig. 4 (a,b) shows the wear rate and friction coefficient of homogeneous and multilayer coatings. The Ni-W multilayer coating with λ ~0.1 μm (indicated as ML0.1) has shown superior wear resistance and lower friction coefficient compared to the homogeneous counterparts. Presence of tensile residual stresses exaggerates the severity of contact stresses during the sliding and leads to sub-surface cracking and delamination [26], [45], [46]. Higher hardness and lower residual stresses of the multilayer coating have led to its superior wear performance. It is well known that the toughness along with the strength play an important role in improving the wear resistance of the coatings [47], [48].

A mere improvement in the hardness renders the brittleness and consequent failure of the coatings at higher loads. Since, the multilayers are composed of alternate hard and soft Ni-W layers, we expect the toughness of these multilayers to be higher than the homogeneous hard Ni-W coating [49] which might have assisted in the improvement of tribological properties.

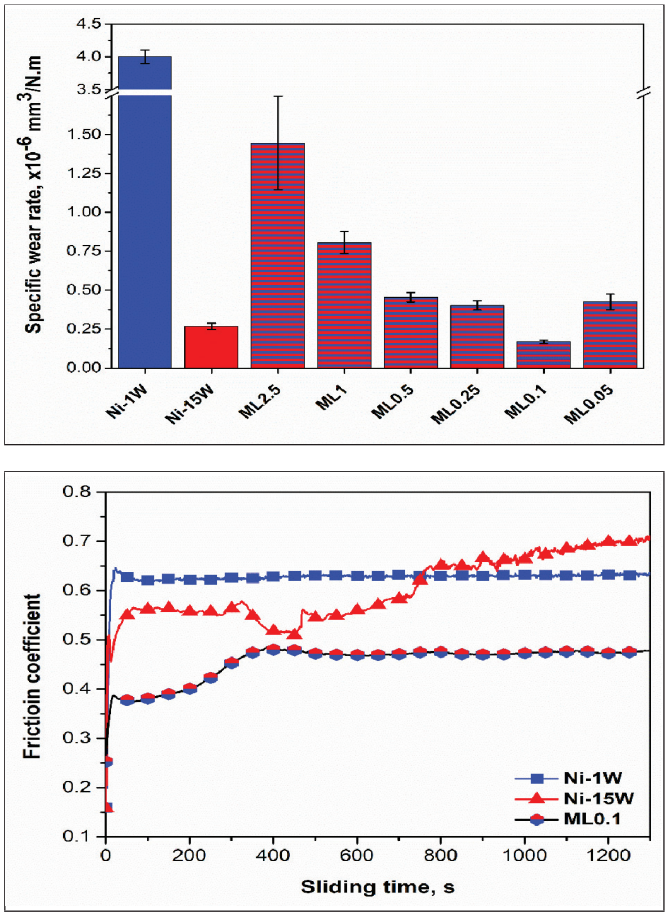


Fig. 4 (a) Specific wear rate and (b) friction coefficient values of homogenous coatings and multilayer coatings determined using the ball-on-disc configuration.

3.4 Influence of layering on thermal properties and wear behavior

During the sliding contact, almost all the frictional energy is converted into heat [50]. This heat, except at very low speeds, leads to an appreciable temperature raise. The highest temperature during the sliding is expected to be located at the true contact regions i.e., the asperities. The raise in the temperature at the contact interface affects the frictional properties of various materials due to the formation of various types of oxides, local phase transformations and sometimes even interface melting. Thus, thermal properties play a crucial role in controlling the wear resistance of materials. For better performance, it is important for the materials to effectively dissipate this heat energy during the sliding contacts. The electrical resistivity of the coatings was measured using the four-probe technique. Later, by applying the Wiedemann-Franz law, the electrical resistivity is converted to the thermal conductivity and thermal diffusivity as per the formulae below [51], [52]:

$$\kappa = \frac{L\,T}{\rho} \qquad \text{--------- Eq. (1)}$$

$$\alpha = \frac{\kappa}{d\,C_p} \qquad \text{--------- Eq. (2)}$$

Where; κ = Thermal conductivity, L = Lorentz number, T = absolute temperature and ρ = electrical resistivity, α = thermal diffusivity, C_p = specific heat capacity and d = density. At room temperature, L $T = 7.5\times10^{-6}$ W.Ω/°K. Since, specific heat capacity and density are structure-insensitive properties, they were calculated using the rule of mixtures. Table 2 provides the calculated electrical and thermal properties of homogeneous and multilayer coatings. Evidently, the multilayer coatings have exhibited higher thermal diffusivity compared to the hard Ni-15W coating.

The kinetics of effective heat dissipation to establish the quasi-steady-state condition is often represented by a dimensionless parameter called Peclet number (P), given as [50]:

$$P = \frac{\upsilon\, r}{2\alpha} \qquad \text{--------- Eq. (3)}$$

Where, υ = velocity of the heat source i.e., sliding speed, r = contact radius which can be calculated using the Hertzian contact model [61], [67]. Essentially, Peclet number (P) is the ratio of true velocity to speed of heat flow. The contact radius calculated for the present experimental conditions is ~40 μm. The computed Peclet numbers for homogeneous and multilayers coatings are given in Table 2. P<0.1 is considered as a regime of very slow sliding speeds where the frictional heat has sufficient amount of time to be dissipated effectively to the surroundings and the system attains quasi-

stationary regime [53]. While, $P>5$ is considered as a regime of high sliding speeds, and the system is not allowed to dissipate the heat effectively resulting in adiabatic heating. From Table 2, it can be observed that the homogeneous Ni-15W has the highest Peclet number and therefore is expected to experience relatively higher interfacial heating and oxidation. It is the rate of generation of oxide and its subsequent detachment from the interface, which determines wear rate. When oxide film is formed steadily and is intact (which is the case of ML0.1), the friction coefficient and wear rate are low. On the other hand, higher rate of oxidation due to extreme heat generation (which is the case of Ni-15W), it is unlikely that oxide film is intact resulting in higher wear rates. In fact, the wear track analysis of the homogeneous Ni-15W indicated the higher amount of oxidation compared to the multilayer coating (ML0.1) providing direct evidence on the effect of the thermal properties. Besides the thermal diffusivity, hardness of the material also affects the extent of raise in the interfacial temperature [50].

Table. 2. Electrical and thermal properties of homogeneous and multilayer Ni-W coatings

The Peclet numbers and therefore, the maximum raise in the interface

Nomenclature	Electrical resistivity x10^{-7} (Ω.m)	Thermal conductivity (W/m.K)	Thermal diffusivity ×10^{-2} (cm^2/s)	Peclet number (*P*)
Ni-1W	2.5 ± 0.9	29.6 ± 1.0	7.28	0.412
Ni-15W	10.9 ± 1.0	6.9 ± 0.7	1.38	2.164
ML2.5	2.6 ± 0.2	29.0 ± 2.0	6.34	0.473
ML0.1	2.8 ± 0.2	26.7 ± 1.5	5.84	0.514

temperature can be compared directly only if their hardness values are in the same range, which is true for homogeneous Ni-15W and multilayer coating. Thus, for similar hardness values and sliding velocity, the value of P is determined by thermal diffusivity. The lower P in case of multilayer coatings is due to higher thermal diffusivity. It has been observed by Lim and Ashby [54] that friction coefficient decreases with decrease in P. Thus, lower wear rate and friction coefficient in case of multilayered coatings compared to Ni-15W is due to their higher thermal diffusivity and lower residual stresses.

4. Conclusions

Exploiting the advantage of reverse/anodic pulsed current, Ni-W multilayer coatings comprised of alternate soft and hard Ni-W layers with layer thickness (λ) ranging from ~2.5 μm to 0.05 μm have been deposited from a single electrodeposition bath. The multilayer coatings have shown a substantial reduction in the residual stresses. The multilayering architecture has allowed to deposit hard coatings with lower residual stresses. Despite the similar hardness, Ni-W multilayer coating (λ ~0.1 μm) has demonstrated superior wear resistance compared to the homogeneous Ni-W coating. The enhanced wear resistance of multilayer coating is attributed to lower residual stresses and relatively higher thermal diffusivity. The multilayer coating has shown lower friction coefficient due to the presence of thin and adherent oxide film.

References

[1] C. A. Ross, 'Electrodeposited Multilayer Thin Films', *Annual Review of Materials Science*, 2003, 24(1), 159–188.

[2] I. Bakonyi and W. E. G. Hansal, 'Development of pulse-plating technology for the preparation of coatings with varying composition along their thickness: a historical overview', *Transactions of the Institute of Metal Finishing*, 2018, 96(5), 237–243.

[3] M. Aliofkhazraei *et al.*, 'Development of electrodeposited multilayer coatings: A review of fabrication, microstructure, properties and applications', *Applied Surface Science Advances*, vol. 6. Elsevier B.V., Dec. 01, 2021. doi: 10.1016/j.apsadv.2021.100141.

[4] A. Sáenz-Trevizo and A. M. Hodge, 'Nanomaterials by design: A review of nanoscale metallic multilayers', *Nanotechnology*, vol. 31, no. 29, May 2020, doi: 10.1088/1361-6528/ab803f.

[5] J. S. Koehler, 'Attempt to design a strong solid', *Phys Rev B*, vol. 2, no. 2, pp. 547–551, 1970, doi: 10.1103/PhysRevB.2.547.

[6] A. S. M. A. Haseeb, 'Dual-Bath Electrodeposition of Cu/Ni Compositionally Modulated Multilayers', *J Electrochem Soc*, vol. 141, no. 1, p. 230, 1994, doi: 10.1149/1.2054689.

[7] K. Matsuoka, M. Okuhata, and M. Takashiri, 'Dual-bath electrodeposition of n-type Bi-Te/Bi-Se multilayer thin films', *J Alloys Compd*, vol. 649, pp. 721–725, 2015, doi: 10.1016/j.jallcom.2015.07.166.

[8] N. V. Myung, K. H. Ryu, J. H. Kim, M. Schwartz, and K. Nobel, 'Electrodeposition of NiFe thin films and NiFe/Cu multilayers with a recirculating electrochemical flow reactor', *Mat. Res. Soc. Symp. Proc.*, vol. 562, pp. 1–4, 1999.

[9] S. Esmaili, M. E. Bahrololoom, and K. L. Kavanagh, 'Electrodeposition, characterization and morphological investigations of NiFe/Cu multilayers prepared by pulsed galvanostatic, dual bath technique', *Mater Charact*, vol. 62, no. 2, pp. 204–210, 2011, doi: 10.1016/j.matchar.2010.11.017.

[10] W. Blum, 'Deposition of Ni/Cu multilayers by dual-bath technique', *Trans. of American Electrochemical society*, vol. 40, pp. 307–320, 1921.

[11] N. IBL, 'Some theoretical aspects of pulse electrolysis', *Surface Technology*, vol. 10, pp. 81–104, 1980.

[12] M. S. Chandrasekar and M. Pushpavanam, 'Pulse and pulse reverse plating-Conceptual, advantages and applications', *Electrochim Acta*, vol. 53, no. 8, pp. 3313–3322, 2008, doi: 10.1016/j.electacta.2007.11.054.

[13] K. S. R. Krishnan, K. Srinivasan, and S. Mohan, 'Electrodeposition of compositionally modulated alloys - An overview', *Transactions of the Institute of Metal Finishing*, vol. 80, no. 2, pp. 46–48, 2002, doi: 10.1080/00202967.2002.11871430.

[14] F. C. Walsh, 'The continued development of multilayered and compositionally modulated electrodeposits', *Transactions of the IMF*, vol. 100, no. 5, pp. 1–12, Jul. 2022, doi: 10.1080/00202967.2022.2094078.

[15] T. J. Rupert and C. A. Schuh, 'Sliding wear of nanocrystalline Ni–W: Structural evolution and the apparent breakdown of Archard scaling', *Acta Mater*, vol. 58, no. 12, pp. 4137–4148, 2010, doi: 10.1016/j.actamat.2010.04.005.

[16] A. J. Detor and C. A. Schuh, 'Tailoring and patterning the grain size of nanocrystalline alloys', *Acta Mater*, vol. 55, pp. 371–379, 2007, doi: 10.1016/j.actamat.2006.08.032.

[17] N. P. Wasekar and G. Sundararajan, 'Sliding wear behavior of electrodeposited Ni-W alloy and hard chrome coatings', *Wear*, vol. 342–343, pp. 340–348, 2015, doi: 10.1016/j.wear.2015.10.003.

[18] M. H. Allahyarzadeh, M. Aliofkhazraei, A. R. Rezvanian, V. Torabinejad, and A. R. S. Rouhaghdam, 'Ni-W electrodeposited coatings: Characterization, properties and applications', *Surf Coat Technol*, vol. 307, pp. 978–1010, 2016, doi: 10.1016/j.surfcoat.2016.09.052.

[19] T. D. Ziebell and C. A. Schuh, 'Residual stress in electrodeposited nanocrystalline nickel-tungsten coatings', *J Mater Res*, vol. 27, no. 9, pp. 1271–1284, 2012, doi: 10.1557/jmr.2012.51.

[20] M. A. Meyers, A. Mishra, and D. J. Benson, 'Mechanical properties of nanocrystalline materials', *Prog Mater Sci*, vol. 51, no. 4, pp. 427–556, 2006, doi: 10.1016/j.pmatsci.2005.08.003.

[21] T. Yamasaki, 'High-strength nanocrystalline ni-w alloys produced by electrodeposition and their embrittlement behaviors during grain growth', *Scr Mater*, vol. 44, pp. 1497–1502, 2001, doi: https://doi.org/10.1016/S1359-6462(01)00720-5.

[22] T. Yamasaki, N. Oda, H. Matsuoka, and T. Fukami, 'Tensile strength of electrodeposited nanocrystalline Ni-W alloys with finely dispersed micrometer-sized array through-holes', *Materials Science and Engineering A*, vol. 449–451, pp. 833–835, Mar. 2007, doi: 10.1016/j.msea.2006.02.410.

[23] J. Li, Q. Zhang, R. Huang, X. Li, and H. Gao, 'Towards understanding the structure–property relationships of heterogeneous-structured materials', *Scr Mater*, vol. 186, pp. 304–311, 2020, doi: 10.1016/j.scriptamat.2020.05.013.

[24] E. Ma and T. Zhu, 'Towards strength–ductility synergy through the design of heterogeneous nanostructures in metals', *Materials today*, vol. 20, no. 6, pp. 323–331, 2017.

[25] D. Vijay Kumar and M. J. N. V. Prasad, 'Pulsed electrodeposition and hardness of microstructurally graded iron', *Surf Coat Technol*, vol. 342, pp. 121–128, May 2018, doi: 10.1016/j.surfcoat.2018.03.001.

[26] L. Bathini, M. J. N. V. Prasad, and N. P. Wasekar, 'Development of continuous compositional gradient Ni-W coatings utilizing electrodeposition for superior wear resistance under sliding contact', *Surf Coat Technol*, vol. 445, p. 128728, Sep. 2022, doi: 10.1016/j.surfcoat.2022.128728.

[27] S. Lee, M. Choi, S. Park, H. Jung, and B. Yoo, 'Mechanical properties of electrodeposited Ni-W thin films with alternate W-rich and W-poor multilayers', *Electrochim Acta*, vol. 153, pp. 225–231, 2015, doi: 10.1016/j.electacta.2014.11.190.

[28] A. W. Ruff and D. S. Lashmore, 'Effect of layer spacing on wear of Ni/Cu multilayer alloys', *Wear*, vol. 151, no. 2, pp. 245–253, 1991, doi: 10.1016/0043-1648(91)90252-P.

[29] S. K. Ghosh, P. K. Limaye, S. Bhattacharya, N. L. Soni, and A. K. Grover, 'Effect of Ni sublayer thickness on sliding wear characteristics of electrodeposited Ni/Cu multilayer coatings', *Surf Coat Technol*, vol. 201, no. 16–17, pp. 7441–7448, May 2007, doi: 10.1016/j.surfcoat.2007.02.014.

[30] C. A. Vlaic *et al.*, 'Improved wear resistance of alternating amorphous and crystalline layers in electrodeposited Ni-P multilayers', *Surf Coat Technol*, vol. 386, Mar. 2020, doi: 10.1016/j.surfcoat.2020.125470.

[31] A. Karimzadeh, A. S. Rouhaghdam, M. Aliofkhazraei, and R. Miresmaeili, 'Sliding wear behavior of Ni–Co–P multilayer coatings electrodeposited by pulse reverse method', *Tribol Int*, vol. 141, Jan. 2020, doi: 10.1016/j.triboint.2019.105914.

[32] V. D. Papachristos, C. N. Panagopoulos, P. Leisner, M. B. Olsen, and U. Wahlstrom, 'Sliding wear behaviour of Ni-P-W composition-modulated coatings', *Surf Coat Technol*, vol. 105, pp. 224–231, 1998, doi: https://doi.org/10.1016/S0257-8972(98)00459-9.

[33] V. Torabinejad, M. Aliofkhazraei, A. Sabour Rouhaghdam, and M. H. Allahyarzadeh, 'Tribological Behavior of Electrodeposited Ni-Fe Multilayer Coating', *Tribology Transactions*, vol. 60, no. 5, pp. 923–931, Sep. 2017, doi: 10.1080/10402004.2016.1230687.

[34] V. Torabinejad, M. Aliofkhazraei, A. S. Rouhaghdam, and M. H. Allahyarzadeh, 'Tribological properties of Ni-Fe-Co multilayer coatings fabricated by pulse electrodeposition', *Tribol Int*, vol. 106, pp. 34–40, Feb. 2017, doi: 10.1016/j.triboint.2016.10.025.

[35] M. H. Allahyarzadeh, M. Aliofkhazraei, A. S. Rouhaghdam, H. Alimadadi, and V. Torabinejad, 'Mechanical properties and load bearing capability of nanocrystalline nickel- tungsten multilayered coatings', *Surf Coat Technol*, vol. 386, p. 125472, 2020, doi: 10.1016/j.surfcoat.2020.125472.

[36] N. Udompanit, P. Wangyao, S. Henpraserttae, and Y. Boonyongmaneerat, 'Wear response of composition-modulated multilayer Ni-W coatings', in *Advanced Materials Research*, 2014, vol. 1025–1026, pp. 302–309. doi: 10.4028/www.scientific.net/AMR.1025-1026.302.

[37] M. V. N. Vamsi, N. P. Wasekar, and G. Sundararajan, 'Influence of heat treatment on microstructure and mechanical properties of pulse electrodeposited Ni-W alloy coatings', *Surf Coat Technol*, vol. 319, pp. 403–414, 2017, doi: 10.1016/j.surfcoat.2017.03.074.

[38] A. J. Detor and C. A. Schuh, 'Grain boundary segregation, chemical ordering and stability of nanocrystalline alloys: Atomistic computer simulations in the Ni-W system', *Acta Mater*, vol. 55, no. 12, pp. 4221–4232, Jul. 2007, doi: 10.1016/j.actamat.2007.03.024.

[39] N. P. Wasekar, A. P. O'Mullane, and G. Sundararajan, 'A new model for predicting the grain size of electrodeposited nanocrystalline nickel coatings containing sulphur, phosphorus or boron based on typical systems', *Journal of Electroanalytical Chemistry*, vol. 833, no. May 2019, pp. 198–204, 2019, doi: 10.1016/j.jelechem.2018.11.057.

[40] N. P. Wasekar, P. Haridoss, S. K. Seshadri, and G. Sundararajan, 'Influence of mode of electrodeposition, current density and saccharin on the microstructure and hardness of electrodeposited nanocrystalline nickel coatings', *Surf Coat Technol*, vol. 291, pp. 130–140, 2016, doi: 10.1016/j.surfcoat.2016.02.024.

[41] A. M. El-Sherik, J. Shirokoff, and U. Erb, 'Stress measurements in nanocrystalline Ni electrodeposits', *J Alloys Compd*, vol. 389, no. 1–2, pp. 140–143, Mar. 2005, doi: 10.1016/j.jallcom.2004.08.010.

[42] P. S. Prevey, 'X-Ray Diffraction Residual Stress Techniques', in *Materials Characterization*, vol. 10, ASM International, 1986, doi: 10.31399/asm.hb.v10.a0001761.

[43] M. V. N. Vamsi, N. P. Wasekar, and G. Sundararajan, 'Influence of heat treatment on microstructure and mechanical properties of pulse electrodeposited Ni-W alloy coatings', *Surf Coat Technol*, vol. 319, pp. 403–414, 2017, doi: 10.1016/j.surfcoat.2017.03.074.

[44] J. H. Lee, J. T. Oh, Y. C. Kim, and J. H. Lee, 'Stress reduction and enhanced extraction efficiency of GaN-based LED grown on cone-shape-patterned sapphire', *IEEE Photonics Technology Letters*, vol. 20, no. 18, pp. 1563–1565, Sep. 2008, doi: 10.1109/LPT.2008.928844.

[45] G. M. Hamilton, 'Explicit Equations for the Stresses beneath a Sliding Spherical Contact', *Proc Inst Mech Eng C J Mech Eng Sci*, vol. 197, no. 1, pp. 53–59, Jan. 1983, doi: 10.1243/PIME_PROC_1983_197_076_02.

[46] Y. C. Huang, S. Y. Chang, and C. H. Chang, 'Effect of residual stresses on mechanical properties and interface adhesion strength of SiN thin films', *Thin Solid Films*, vol. 517, no. 17, pp. 4857–4861, 2009, doi: 10.1016/j.tsf.2009.03.043.

[47] N. A. A. R. Aly and M. R. El-Koussy, 'Relationship between Ductility and Wear Resistance of High Mn-Steels', in *Surface Engineering*, Dordrecht: Springer Netherlands, 1990, pp. 640–651. doi: 10.1007/978-94-009-0773-7_63.

[48] E. Hornbogen, 'Role of fracture toughness in wear of metals', *Wear*, vol. 33, no. 2, pp. 251–259, 1975, doi: https://doi.org/10.1016/0043-1648(75)90280-X.

[49] F. Liang, Z. X. Wang, Y. W. Luo, B. Zhang, X. M. Luo, and G. P. Zhang, 'Enhancing co-deformation ability of nanograined Ni-W layers in the Ni/Ni-W laminated composites', *Acta Mater*, vol. 216, Sep. 2021, doi: 10.1016/j.actamat.2021.117138.

[50] J. F. Archard, 'The temperature of rubbing surfaces', *Wear*, vol. 2, no. 6, pp. 438–455, 1959, doi: https://doi.org/10.1016/0043-1648(59)90159-0.

[51] S. Wang, I. Brooks, J. McCrea, G. Palumbo, G. Cingara, and U. Erb, 'Thermal conductivity and electrical resistivity in polycrystalline and nanocrystalline nickel', in *Advanced Materials Research*, 2012, vol. 409, pp. 561–565. doi: 10.4028/www.scientific.net/AMR.409.561.

[52] H. J. Cho, S. Wang, Y. Zhou, G. Palumbo, and U. Erb, 'Thermal conductivity of bulk electrodeposited nanocrystalline nickel', *Int J Heat Mass Transf*, vol. 100, pp. 490–496, Sep. 2016, doi: 10.1016/j.ijheatmasstransfer.2016.04.068.

[53] Y. X. Ye, C. Z. Liu, H. Wang, and T. G. Nieh, 'Friction and wear behavior of a single-phase equiatomic TiZrHfNb high-entropy alloy studied using a nanoscratch technique', *Acta Mater*, vol. 147, pp. 78–89, Apr. 2018, doi: 10.1016/j.actamat.2018.01.014.

[54] S. C. Lim, M. F. Ashby, and J. H. Brunton', 'Wear-rate transitions and their relationship to wear mechanisms', *Acta metallurgica*, vol. 35, no. 6, pp. 1343–1348, 1987, doi: https://doi.org/10.1016/0001-6160(87)90016-2.