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Influence Of Silica Content into Nickel/Silica Electrodeposited Composite Coating for Mechanical and Corrosion Resistant Properties Enhancement: A Review

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Abstract

The ratio cost/efficiency of electrodeposited composite coating has boosted the development of this method in the last decades. Thus, electrodeposited nickel with silica particles as reinforcement was successfully designed and the conditions to increase particles in the composite are better understood. Those composites' morphological, mechanical, and corrosion properties as a function of the embedded silica particles were also investigated. In this review, the last findings about nickel/silica preparations and their properties are specifically summarized. Data collected here indicate that silica particles entrapment depends on current density, particle load in the bath, particle surface modification, and hydrodynamics. The presence of silica particles in the composite led to the refinement of the nickel grain and consequently enhanced the mechanical and corrosion properties.

Keywords: Electrodeposition, Nickel, Silica, Mechanical properties, Corrosion

INTRODUCTION

Interactions between materials and their environments occur through their surfaces with thicknesses of about ten microns (Giurlani, et al., 2020). Degradations or passivation may result due to phases in the presence and the physical chemistry conditions. When the material is not solicited in bulk, only surfaces are affected, leading to the failure of the material. Among many alternatives and strategies, electrodeposition of composite coatings is the most used since this technique is cheap, easy to handle, technically accessible, and experimentally comprehensive. In addition, the electrodeposition technique produces less waste than other methods (Stojak & Talbot, 1999). Electrodeposited Composite Coatings (ECC) contain the simultaneous electrodeposition of metal and solid particles onto a substrate. Then, ECC allows the production of new and cheap materials with enhanced surface properties and specific functions. The proof of enhancement due to particles in the metal matrix electrodeposited has given great attention to this method.

Generally, steel substrates are the most plated (Abro et al., 2023; Tuaweri & Wilcox, 2006) because they are primarily used for human metallic needs and are subject to degradation (Dable & Abro, 2020; Misriyani et al., 2015). To increase the lifetime of equipment, the choice of metal to be deposited must and respond to the plating criteria. Crystal lattices of the deposited material must correspond to the substrate and present better properties for the purposes for which it is deposited. These reasons have led to the increasing use of nickel as an electrodeposited metal. Nickel is a face-centered cubic metal, stable in organic solvents, and possesses good electrical and thermal properties. It is also corrosion-resistant, and has a bright finish compared to Copper (Wen et al., 2024a), Zinc (Khan et al., 2011a; Kondo et al., 2000) , and Magnesium

The particles can be classified as polymers (PTFE) (Li, et al., 2024a; Wang et al., 2023a), carbides (C, SiC, WC, Diamond) (Rao et al., 2023b; et al., 2021b), and oxides (TiO_2, Al_2O_3, SiO_2) (Ratajski et al., 2018a).

While the carbides are mostly co-deposited to improve the mechanical properties of metal electrodeposited, oxide particles are used for anti-corrosion purposes, although both weaknesses can be remedied concurrently. In modern technology, silica ceramics are used in various fields of thermoelectric devices (Wu et al., 2017), batteries (Wen et al., 2024), energy (Nguyen, 2007), microelectronics (N. V. Bogomazova et al., 2014a), wear (Liu 2011a), optics, and magnetic devices (Narvaez, Dominguez, Martinez, & Ruiz, 2003) with improved mechanical properties and corrosion-resistant ability of pieces of equipment.

The idea behind using silica ceramic particles in electrodeposited nickel/silica material is to take advantage of the oxide type of these particles to decrease the corrosion rate of the protected surfaces. The large distribution of silica particles spread on the surface the most efficient the coating against corrosion. According to Khan et al., (2011a) one can distinguish three types of particle electrodeposition, namely (i) adsorption, (ii) Entrapment, and (iii) incorporation (Figure 1).

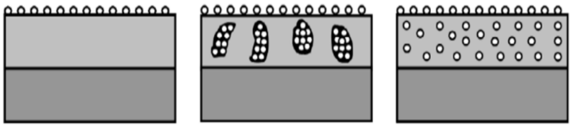
a) Particles adsorbed on the coating ("Adsorption")
b) Particles entrapped inside the coating ("Entrapment")
c) Particles embedded inside coating ("Incorporation")

Figure 1. Different types of codeposition (Khan et al., 2011)

The third configuration, in which particles are homogeneously distributed in the coating layer without agglomeration as well as onto the surface, is the most desired. However, the first attempts to codeposit silica with nickel through nickel electrolyte resulted in poor incorporation of particles (Bogomazova et al., 2014a; Nowak et al., 2000) with poor reproducibility.

Based on the means of electrochemical impedance spectroscopy, it has been shown that the presence of silica at the cathode substrate increases its specific capacitance. The electrical barrier that exists impedes particles for being close enough to the cathode to facilitate the codeposition. This barrier takes the form of a thick liquid layer larger than the electrical double layer, which maintains a constant distance between silica particles and the cathode, making it difficult the incorporation of particles. The study of the surface chemistry of silica particles in liquid reported by Zhuravlev (2000a) indicates the presence of silanol groups, which make them hydrophilic. This silanol establishes strong hydrogen bonds with water molecules so that silica particles remain far from the substrate and the probability of their electrocodeposition drastically decreases. This is why, despite very good properties, ECCs of nickel with silica particles are not the most published (Mahidashti et al., 2018a)

Several studies have focused on increasing the amount of silica particles and the particle dispersion in the coating by different approaches. The goal is to improve the mechanical and corrosion properties of silica-reinforced nickel electrodeposited. Then, the effect of the current density, the hydrodynamics of the bath, the silica particle types and/or size, the surface modification by surfactants, and the load of particles in the bath have been investigated. Despite all these possible applications, and the fact that silica material is the most abundant component of the Earth's crust (Sulpizi et al., 2012a), the number of papers reporting nickel/silica remains lower than other composites, such as silicon carbide (SiC).

Many reviews have been published on the electrodeposited composite of metal/particle. Even the recent review papers mostly summarize the mechanical properties of composite coatings embedding oxide particles such as ZrO_2, TiO_2, or Al_2O_3 as the second phase element (Mahidashti et al., 2018a; Raghavendra et al., 2018). For example, the presence of Al_2O_3 39 vol.% allows double the microhardness of the nickel matrix. Likewise, Dhakne et al., (2022a) provide an update on the wear and tribology improvement of magnesium alloy due to the presence of silica in the nickel electrodeposition. However, a specific review dealing with nickel/silica preparation and its properties is missing to the best of our knowledge (Ahmad & Mohamed, 2014a; Mahidashti et al., 2018a; Raghavendra et al., 2018). This review pays particular attention to the latest developments in nickel/silica electrodeposited composite coatings and how they improve mechanical and corrosion properties.

METHODOLOGY

Production of silica particles

Although silica can be obtained from coal fly ashes (Hanum et al., 2022), the literature reports essentially that silica particles can be obtained by the two methods, which are the physical (grinding) and the chemical (sol-gel, chemical vapor condensation, and reverse microemulsion) methods. The sol-gel process is well-known as the Stober method (Stöber et al., 1968a). However, biological silica has now been produced.

Grinding method

First, silica particles are obtained by grinding in different types of mills such as oscillating mills, planetary mills, vibration mills, jet mills, or ball mills with iron (Nowak et al., 2000; Samayamutthirian et al., 2007). In the case of ball mills, high-purity quartz sand is ground with iron balls. After the grinding step, the particles obtained are washed in nitric acid and rinsed in water to remove residual iron in the produced powder. According to the type of grinding and the mills, particles with mean diameters between 0.4 and about 5 microns are obtained (Nowak et al., 2000).

STOBER method

The production of silica particles by the method of Stöber consists of the hydrolysis and condensation of tetraethyl orthosilicate $Si(OC_2H_5)_4$ (TEOS) in a mixture of ammonia, ethanol, and water through a sol-gel process (Narayan et al., 2018a; Stöber et al., 1968a; Terzieva et al., 2000). This inexpensive, low-temperature, and controlled technique allows the formation of uniformly dispersed silica particles at the nanoscale.

The typical scheme of this method can be summarized in Figure 2.

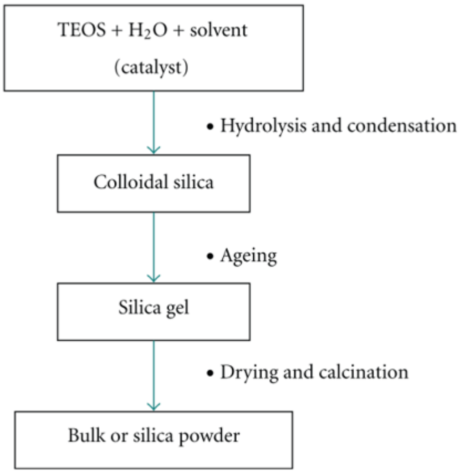

Figure 2. Typical sol-gel process
(Rahman & Padavettan, 2012)

Silica particles first nucleate by hydrolysis and then grow during the condensation steps. Many studies reported that the size of silica nanoparticles synthesized by this method could be controlled by the type of alcohol, the anion electrolyte additives, and the process modes. For example, silica particles synthesized in ethanol are smaller than those obtained in methanol, so that a 7.9 nm size was produced (Green et al., 2003).

Biosilica production

The biomass can also be used to produce silica particles. The proof of that technique using rice husk has been given recently Mladenović et al., (2024). Rice husks were first cleaned with water, dried, and treated in 10% sulfuric acid at 80 °C for 3 h. This process produces silica particles. Following this, the husks were washed in purified water until a neutral reaction was achieved and dried at 50 °C for further treatment. A Bunsen flame is used to burn the shells. The obtained substance is heated to 900 °C in a furnace for 4 h, producing a white biosilica powder having an amorphous structure. The process steps are depicted in Figure 3.

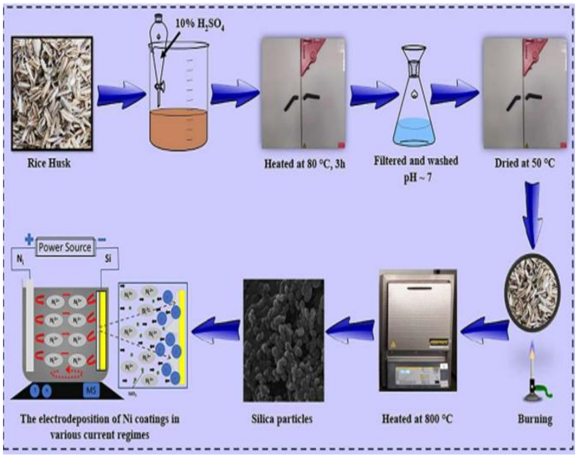

Figure 3. Bioprocess of silica nanoparticles production
(Mladenović et al., 2024)

The benefit of this process is the less use of chemicals and not heavy equipment, making this a green chemistry method. Because the deposit of biomass is huge and diverse, this method is viable. For example, Sunarti et al., (2023) reported that the palm shells and coir ash, which can be used to synthesize silica gel, contain approximately 76% of SiO_2.

Silica Colloids Stability

Use of Surfactants - zeta potential

It is well known that nanoparticles are subjected to agglomeration due to their high surface charge. Thus, low dispersion of particles in the coatings occurs and so a bad codeposition which may negatively influence the properties of the coatings. Surfactants are commonly used to decrease the surface tension of silica particles. The zeta potential (Abro et al., 2016) , which is the static electricity force, allows for the assessment of the surface charge of particles immersed in an electrolyte medium. In nickel baths, silica particles exhibit a negative surface charge (Ratajski et al., 2016a; Xu et al., 2005) of about -5.5

mV at pH around 4 (Xu et al., 2005). However, the use of cationic surfactants, for example, Golub et al., (2004) changes the charge of silica particles to positive. The particles become dispersed enough in the bath, the colloids' stability (Xu et al., 2005) is improved as well as the distribution of particles into the composite. Polyethylamine (PEI), sodiumdodecylsulfate (SDS) (Miyamoto et al., 2010b), polydiallydimethylammonium chloride (PDDA) (Ratajski et al., 2018a), Cetyltrimethylammonium bromide (CTAB) (Nikolaus & Martin, 2011; Parida et al., 1999) surfactants, among others, (Rouhollahi et al., 2018a) have been recently used for nickel/silica coatings preparations.

Deep eutectic solvent

Liquid electrolytes have been commonly used for nickel composite electrodeposition with particles. These electrolytes are usually prepared by dissolving a molar of the metal salt. They present a high ionic strength, a good viscosity, and are thermally stable. However, colloidal baths of nano nickel/silica particles are not stable. Indeed, one of the consequences of the agglomeration of particles is their settling once the density of the agglomerates exceeds that of the water. This is why electrodeposition baths are constantly stirred to keep particles suspended, to increase the probability of embedment. To improve nickel/silica particles colloids, deep eutectic solvents (DES) are increasingly used (Li, et al., 2016a; Mernissi Cherigui et al., 2017a; Smith et al., 2014a). DES are non-toxic, cheap, easy to prepare, and allow good dispersion of particles (Smith et al., 2014). A deep eutectic solvent improved the stability of the nickel/silica colloids up to 30 h instead of 30 minutes (Xu et al., 2005).

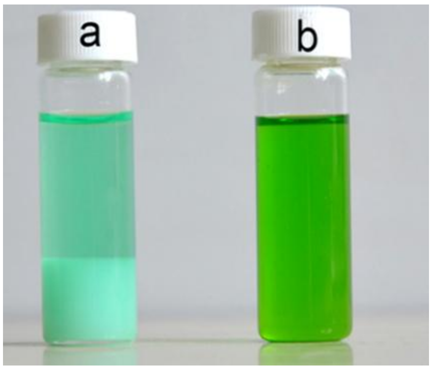

Figure 4. Settling down of silica particle (a), Stability of a 25 g/L nickel/silica colloid dispersed in a deep eutectic solvent (b) (Li et al., 2016a)

The general formula of DES is $Cat^+X^-{}_zY$ (Smith et al., 2014) , where Cat^+ represents the halide salt, X^- a Lewis base which is a hydrogen bond donor, Y a Lewis or Bronsted acid, and z indicates the number of Y involved in the solvent. In practice, the halide to the hydrogen bond donor molar ratio is 1/2.

The common compositions for nickel and silica codeposition through DES have concerned Choline chloride (ChCl) and Ethylene Glycol (Fattah et al., 2020a; Li et al., 2016; Li et al., 2016a).

RESULTS AND DISCUSSION

Strategies for particle embedment increase in the composite

Since the presence of particles, such as silica, in the nickel matrix has been proven to enhance the mechanical and corrosion properties of a nickel/silica composite coating, great attention has been paid to improving the rate of particles in the composite coating. Then, different strategies were employed. In this review, surface modification by surfactants, the current density, the quantity of particles loaded in the bath, and the hydrodynamics effects are investigated.

Surface modification by hydrophilization of silica particles

The hydrophilic characteristic of silica particles is pointed out as the main reason for its poor co-deposition through aqueous electrolyte (Nowak et al., 2000; Rouhollahi et al., 2018; Terzieva et al., 2000). The surface chemistry of silica particles in an aqueous bath presents the formation of strong bonds between hydroxyl silanol groups located on the surface and water molecules (Zhuravlev, 2000). This wettability state is so detrimental for silica entrapment into nickel electrodeposition. Surfactants are employed to promote their adsorption onto particles to alter this wettability and to increase the electrophoretic motion in the double layer. In the aqueous medium, cationic surfactants (Zamblau et al., 2011) first dissolve into a hydrophobic part, usually an aliphatic chain and a hydrophilic charged head. The aliphatic chain adsorbs on particles (Golub et al., 1996) and breaks the aqueous film around silica particles. Due to its acidic character (Sulpizi et al., 2012), in acidic electrolytes with pH around 4 (Abro et al., 2017; Kasturibai & Kalaignan, 2012a; Wang et al., 2016), commonly used for nickel electrodeposition, silanol groups on silica particles release protons according to Bronsted. So only, the adsorption of the aliphatic chain of the cationic surfactant alters the wettability of silica as shown by Bi et al., using the cetyltrimethylammonium bromide (CTAB) (Bi et al., 2004a; Ghazanlou et al., 2018). Then, cetyltrimethyl ammonium chloride (CTAC) cationic surfactant allows to embedding more than 9 vol% of silicon dioxide (Rouhollahi et al., 2018), while the use of 3 mL/L of polydiallydimethylammonium chloride (PDDA) allowed for embedding 27 vol% (Ratajski et al., 2020). A sketch of CTAB adsorption in the nickel bath is shown in Figure 5.

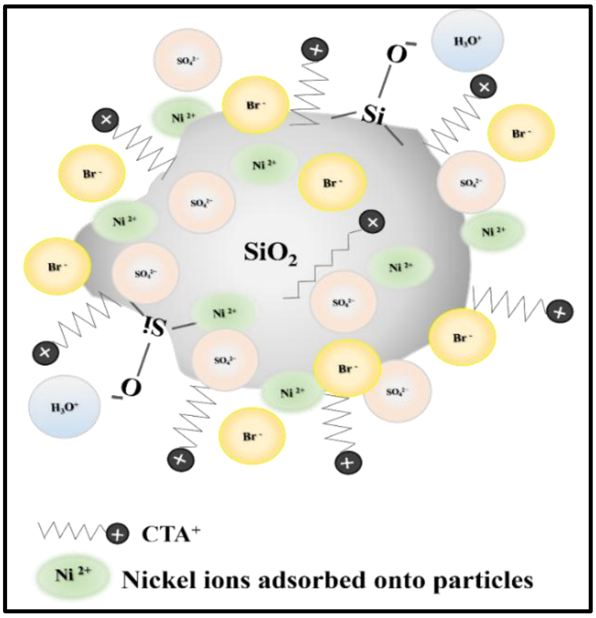

Figure 5. Sketch of CTAB adsorption on silica particles in a nickel sulphate bath

Current density or deposition potential

Electrodeposition of nickel is conducted by applying a fixed overpotential (potentiostatic mode) or current density (galvanostatic mode). In both cases, the potential difference applied produces the migration of electroactive species, for example, nickel and hydrogen ions, toward the working electrode for reduction (Abro et al., 2024). The flux of nickel ions that reach the diffusion layer is increased with the current density (Djouani & Qian, 2018), and the nucleation and growth (Azizi et al., 2008a), and the morphological (Rashidi & Amadeh, 2008) features of the metal are influenced (Jiang et al., 2021). As an example, the grain size of nickel electrodeposited decreases. Concurrently, inert silica particles got entrapped into the composite during nickel discharging whatever the position vertical or horizontal of the working electrode. Then, the silica content in nickel coatings increases (Jiang et al., 2021). Likewise, Abro *et al*. reported that an increase of the potential from -1.15 V/ECS to -1.4 V/ECS allows to increase the silica embedment from 2 to 34 vol% (Abro, et al., 2023).

Table 1. Summary of maximum silica entrapped for different particle loads.

No	Maximum Silica load (g/L)	Silica embedded amount	Silica particle distribution (nm)	Bath type	Bath agitation	Surfactant	References
1	12.0	4.60 wt%	1000	Aqueous	Magnetic stirring	Yes	(Kasturibai & Kalaignan, 2012a)
2	13.2	2.27 wt%	50-70	Aqueous	Not indicated	No	(Bogomazova et al., 2014a)
3	25.0	4.69 wt%	15-30	DES	Magnetic stirring	No	(Li et al., 2016a)
4	10.0	0.85 at%	20-30	Aqueous	Jet	No	(Wang et al., 2016b)
5	20.0	1.80 vol%	200	Aqueous	Magnetic stirring	Yes	(Rouhollahi et al., 2018)

Hydrodynamics

Particles to be embedded must be in the vicinity of the working electrodes before being entrapped in the growing material. Then, they must migrate before reaching the diffusion layer where the electrophoresis phenomenon undergoes. At this point, it is important to distinguish magnetic and/or ultrasonic stirring that is undertaken to ensure the homogeneity of the suspensions before conducting electrodeposition from that used during the experiment.

In practice, convection is ensured by agitation using in most cases a magnetic stirrer or by the use of jet cells. Magnetic stirring at different speeds brings particles to the cathode in a non-brownian movement (Papadopoulou et al., 2020a) and, maintains constant their quantity in the close environment of the cathode to increase the probability of their embedment. Although very rare studies have dealt with the effects of magnetic stirring on silica particle rate in nickel matrix, certainly due to its bad codeposition (Socha et al., 2004a). However, data reported for other oxide particles, such as alumina Al_2O_3, show that this rate increases with the agitation speed (Jeyaraj et al., 2016). To increase the embedment probability of particles, jet cells using hydrodynamics have been developed. The principle of such systems is to bring, by the means of a directed flow outgoing from a nozzle, particles to the working electrode. Then, the flow rate reduces or contracts the diffusion layer (Vakilipour Takaloo, et al., 2013a), and the stay time of particles decreases allowing the enhancement of particles entrapment. Also, the major feature of electrochemical jet cells is that they allow to correlation between the flow rate and mass transport parameters (Abro et al., 2016; Yihao Wang et al., 2016b). By writing the limiting current as a function of the Reynolds number Re, the mass transfer becomes accessible, Equation 1:

$$i_{lim} = \left(\left(anFCDSc^{\frac{1}{3}}\right)/R\right)Re^{\frac{1}{2}} \qquad (1)$$

With a coefficient, $\boldsymbol{n}$ the number of electrons exchanged, F the Faraday, C the concentration of the electroactive species, D the diffusion coefficient, Sc the Schmidt number.

One of the benefits of the hydrodynamic jet cells is the capability of such systems to control flow rates, mass transfers, and particularly particle shocks with the cathode. In the case of silica particles, the shock enables to removal the aqueous film responsible of the bad co-deposition of those particles.

Then, a silica-reinforced nickel matrix deposited in laminar flow indicates the possible silica entrapment up to 34 vol% (Abro, et al., 2023; Abro et al., 2017; Wang et al., 2016b). This condition is represented in Figure 6.

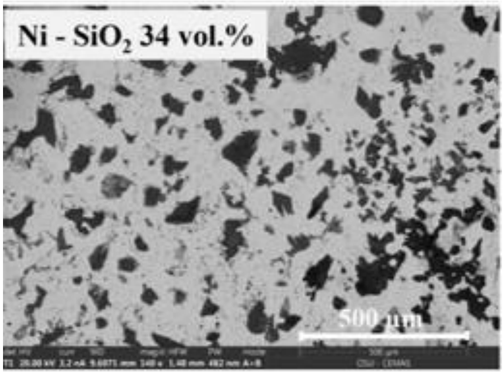

Figure 6. Micrographs of different Ni-SiO_2 composite coatings (Abro, et al., 2023)

Silica Particles load

An interesting but costly in material, way to increase the particle entrapment in the coating is to increase the load in the colloid. The more particles in the bath, the more particles in the diffusion layer, and the more particles adsorb onto the working electrode to undergo codeposition according to the mechanism proposed by Vereecken et al., (2000a) and Bengoa et al., (2016a). In their investigations, particles mass transfer and residence time onto the cathode play a major role. However, up to a certain limit, at a fixed concentration threshold beyond, neither the increase in particles in the suspension nor a greater agitation influences the incorporation of particles into the coating as depicted in Figure 7.

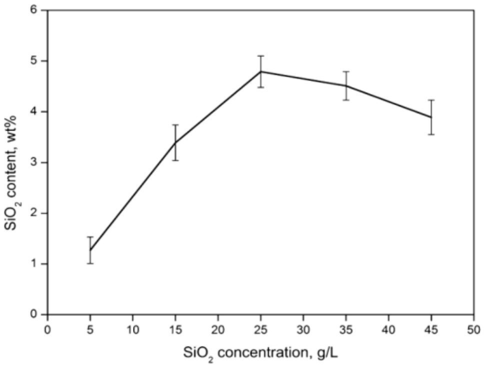

Figure 7. The weight percentage of SiO_2 nanoparticle in the Ni-SiO_2 composite coating is expressed as a function of SiO_2 concentration (Li et al., 2016b)

Table 1 summarizes the particle load that achieves the maximum silica entrapment in the nickel matrix for some references. Based on the data in Table 1, despite the various systems used, it emerges that micro-sized silica entraps easily in the presence of surfactant in an aqueous bath. Thus, 4.60 wt% of particles was embedded with only a load of 12 g/L (Kasturibai & Kalaignan, 2012a). This may be due to the fact that the quantity of motion acquired through the bath agitation, higher for micro-sized particles allows efficient shock to the cathode, leading to their embedment. Besides, the colloid stability of Deep Eutectic Solvents also improves the nano-sized silica amount into the nickel matrix because particles are less solvated.

Deposition morphologies

The microstructures of Ni-SiO_2 are not very different from those of Nickel. Usually, pyramidal grains are obtained for low deposition current densities. However, grain refining is generally observed. A higher nucleation rate is induced in the presence of silica nanoparticles (Liu et al., 2011). It results in a compact and uniform composite coating in Figure 8-a. Also, the dendritic growth of the coating can be seen in Figure 8-b.

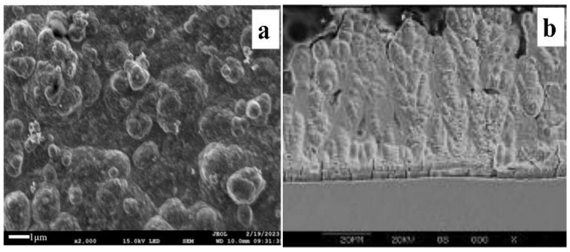

Figure 8. Microstructure of top (a) (Kasturibai & Kalaignan, 2012b) and cross section (b) (Bin-shi et al., 2005) of Ni-SiO_2

Table 2. Effect of silica content on microhardness properties

No	Authors	Year	Coatings	Silica content	Silica particle distribution (nm)	Substrate	Microhardness (GPa)	Ref.
1	Kasturibai *et al.*	2012	Ni	--	1000	Mild steel	2.59	(Kasturibai & Kalaignan, 2012a)
			Ni-SiO_2	4.60 wt%			6.03	
2	Bogomazova *et al.*	2014	Ni	--	50-70	N.I*	2.70	(Bogomazova et al., 2014a)
			Ni-SiO_2	2.27 wt%			3.27	
3	Mladenovic *et al.*	2024	Ni	--	50 – 100	silicon	3.54	(Mladenović et al., 2024)
			Ni-SiO_2	1.00 wt%			4.86	
4	Li *et al.*	2024	Ni-SiO_2	6.36 wt%	8 – 15	Steel	6.07	(Li et al., 2024)

Enhanced properties of Ni-SiO_2 composite

Mechanical Properties

It is noteworthy that the presence of second solid phases in nickel coating improves the mechanical properties of the latter. (Dhakne et al., 2022) proof of enhancement of roughness, wear, friction, and hardness (Wang et al., 2016b) due to particles simultaneously deposited in metal matrix electrodeposited Ni-SiO_2 has given great attention to this composite.

The roughness of Ni-SiO_2 is higher than that of Ni as reported by Mladenović et al., (2024). From their study, nickel and nickel silica root mean square roughness parameters (Rq) are 78.36 nm and 105.40 nm, respectively. Adsorption being a detrimental step for particle entrapment, it may result in addition to pyramidal grains, protrusions, and clusters microstructures (Liu et al., 2024) with a lot of nontotally embedded silica increasing the roughness of the composites. Likewise, the wear and the friction coefficient also increase. Liu et al., (2011a) reported that in such conditions, cracks resulting from wear experiments are limited, wear debris are small, and exfoliation of the composite surface are hindered. The comparison of the microhardness of Ni-SiO_2 to pure nickel coatings for some references is listed in Table 2.

A significant enhancement of this mechanical the parameter for the composite is noticed for each case. During the growth of the composite, the adsorption of micro and nano silica particles onto the working surface induces a topography that confines the growth of nickel nuclei. Yet, the Hall–Petch formula (Rao et al., 2023) indicates that the decrease in grain size led to an increase of the microhardness of the material. In the study of Kasturibai & Kalaignan (2012b) as an example, nickel grain size decreases from 23 nm to 21 nm in the presence of silica particles. Consequently, the microhardness of the coating increases from 2.59 GPa to 6.03 GPa as recorded in Table 2.

On the other hand, the dispersion of silica as a second-phase element into electrodeposited nickel also improves its mechanical features. Although several values of silica microhardness are reported according to the type, the fabrication process, and the size (Bousbaa et al., 2003), it is noteworthy that this ceramic material possesses better mechanical characteristics than nickel metal. Papers reviewed in Table 2 indicate a microhardness varying from 2.59 to 3.54 GPa for nickel, while silica exhibits a microhardness above 6 GPa. Also, Miyamoto et al., (2010) found that the deformation of nickel/silica matrix that may occur through the sliding of grain is impeded by the presence of silica in the nickel grain boundaries. The microhardness as well as the overall mechanical properties are so enhanced.

Corrosion resistance properties

Corrosion of metals and metal alloys represents their chemical dissolution in specific environments, such as those containing sodium chloride. According to the data reported, nickel/silica composite coatings are a good alternative to face this big economic and technical challenge. Ni-SiO_2 is mostly used to overcome uniform corrosion. In this type of degradation, the corrosion rate is constant on the surface exposed to the corrosive environment (Khalaf et al., 2024). Then, the strategy consists of the electrodeposition of the composite onto the entire surface to isolate it. In practice, the protective effect of the composite is determined through the chloride solution NaCl 3.5% which simulates the seawater. By using the TAFEL plot, the corrosion potential and the corrosion current are extracted from experimental data as illustrated in Figure 9.

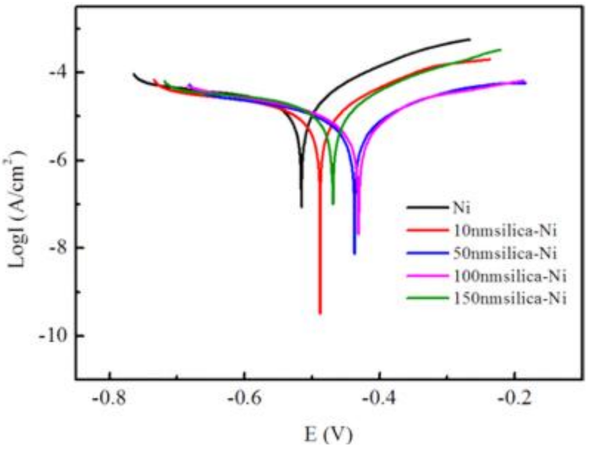

Figure 9. Polarization curves in TAFEL plot of Ni and silica-Ni hybrid layers in 3.5 wt% NaCl solution (Yang et al., 2020b).

The more positive is corrosion potential, the more protective the coating. Table 3 lists corrosion potentials and currents of some important references. For each case, the presence of silica particles in the coating shifts the corrosion potential toward more positive values. However, this variation ΔE (mV/SCE) that indicates the efficiency of the composite in comparison of the nickel is higher for the coating electrodeposited with nanometric particle, and especially in deep eutectic solvent (DES) (Li et al., 2016b). Besides, the corrosion current remains low. In fact, the dispersion of silica onto the surface hinders potential sites of oxidation and the corrosion current decreases. Also, when hydrophobic silica particles are used, the corrosion properties are enhanced because adhesive forces at water/silica interface are low, and the oxidation process is not favoured (Xiang et al., 2016).

The effect of the silica particles size on anti-corrosion efficiency was studied by Yang et al., (2020b) in a 3.5 wt% NaCl solution. Results indicate that the presence of nano silica particles improve the corrosion resistance until a certain size limit of 100 nm. For bigger sizes, any further improvement is observed.

Apart from the uniform corrosion, the pitting corrosion susceptibility of Ni-SiO_2 has also been studied by the mean of a syringe cell for a silica volume percentage content of 0, 2, 4, and 34 (Abro et al., 2023). It was found that after a limit of 2 vol%, heterogeneities in the material increase the initiation of the pits onto the surface. Thus, it can be concluded that despite the anti-corrosion benefit of silica in nickel composite coatings, just a limited number of entrapped particles is necessary to avoid the contrary effect.

Table 3. Summary of corrosion potential and corrosion current conducted in NaCl 3.5 %.

No	Authors	Year	Coatings	Silica Content	Silica particle distribution (nm)	E_{corr} (mV/SCE)	ΔE (mV/SCE)	I cor (µA/cm^2)	Ref.
1	Kasturibai et al.	2012	Ni	-		- 553		89.13	Kasturibai & Kalaignan, 2012b
			$Ni-SiO_2$	4.6 wt%	1000	- 672	-119	1.73	
2	Ruiqian et al.	2016	Ni	-		- 676		39.20	Li, et al. 2016b
			$Ni-SiO_2$	4.7 wt%	15-30	- 386	290	0.28	
3	Wang et al.	2016	Ni	-		- 373		3.58	Wang et al., 2016b
			$Ni-SiO_2$	4.0 g/L	20-30	- 303	70	2.41	
4	Ratajski et al.	2020	Ni	-		- 160		0.44	Ratajski et al., 2016
			$Ni-SiO_2$	18.4 vol%	10-40	- 160	0	0.03	
5	Azem et al.	2024	Ni	-		- 167		0.26	Azem et al., 2024
			$Ni-SiO_2$	3 g/L	50-70	- 124	43	0.18	
6	Jianguo et al.	2024	Ni	-		- 466		30.6	Liu et al., 2024
			$Ni-SiO_2$	≤ 0.05wt% *	20; 1000	- 361	105	0.83	

CONCLUSION

Several general conclusions can be made regarding the production, morphology, mechanical characteristics, and corrosion properties of nickel/silica. From the data exposed in this review, it can be concluded that:

- The surface modification by surfactants, the current density, the number of particles loaded in the bath, and the hydrodynamics play a role in the rate of the particle embedment into the composite coating until a certain limit
- The hydrodynamic jet cell is useful to overcome the hydrophilic feature of silica particles and thus increase the rate of particles in the composite
- The presence of silica particles in the nickel matrix leads to a refinement of nickel grain.
- The refinement of nickel grain with the presence of silica particles in the coating increases the mechanical properties which are the roughness, the wear, and the microhardness
- Nickel/silica composite coating is a good alternative against uniform corrosion and pitting corrosion by increasing the corrosion potential and decreasing the corrosion potential in terms of future work trends
- The use of biological silica may be encouraged to avoid hazards associated with organic compounds
- The increase of silica particles is never the fact of only one parameter at a time but rather the synergetic effects of many. The most relevant are particle load, hydrodynamic and the current density. Then studies using experimental design may strongly help to evaluate the contribution of each of them

The use of Artificial Intelligence to predict the limit of silica content in nickel in correlation with the mechanical and corrosion properties might be conducted.

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