Template- and Magnetic Field-Free Chemical Reduction of Ni Nanochains for Ni–Al₂O₃ Cermet Films: Growth Control, Characterization, and Application

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ABSTRACT: Cermet-based solar absorbers containing nickel (Ni) in a nanochain (NC) structure embedded in an aluminum oxide (Al₂O₃) film demonstrated a high absorptance of more than 90% of the solar spectrum. In this work, Ni NCs were successfully prepared by a simple chemical reduction method without the assistance of a template or magnetic field. The formation of Ni nanoparticles (NPs) in different configurations was controlled by adjusting the NaOH:NiCl₂ molar ratio. Not only was NaOH used to adjust the solution pH but it also induced the reduction reaction to be faster and so resulted in a larger number of Ni nuclei. Together with the intrinsic magnetic property of Ni, Ni NPs tended to orient in a chain-like manner to form Ni NCs that remained stable throughout the reaction. Increasing the NaOH:NiCl₂ molar ratio up to 8 led to a uniform morphology of Ni NCs. However, at higher molar ratios (above 8), the NCs were likely to collapse at the end of the reaction, forming near-globular particles. With its unique structure, metallic Ni NCs were employed by incorporating them into a ceramic layer of Al₂O₃, which can be used as efficient cermet materials. Compared to a conventional cermet with embedded spherical Ni NPs, a 16.4% increase in solar absorptance was observed with the Ni NCs due to their enhanced absorption and scattering in the solar spectrum. Moreover, increasing the Ni NC content in the Al₂O₃ layer gradually enhanced the solar absorptance to 0.91 and so was a good solar absorber.

1. INTRODUCTION

Various forms of nanostructured materials, including nanoparticles (NPs), nanowires, nanotubes, nanorods, etc., have been used in a variety of applications due to their unique morphologies and physical properties. Among the potential applications, solar absorber materials, used as a surface coating for the absorption of incident solar energy and conversion into thermal energy, require a composite material with a high photothermal conversion efficiency and thermal stability at a high temperature.¹ A variety of cermet (ceramic and metal)-based coatings have been investigated since 1980s and still received considerable attention as attractive solar absorbers because of their excellent optical properties and thermal stability.²⁻⁴ In general, cermet coatings consist of a metal in an NP form dispersed in a ceramic matrix. Metals usually have a high infrared reflectance, yet a mismatched refractive index with air, and some of the light is reflected off the surface rather than being absorbed. For this reason, incorporation of metal NPs into a ceramic layer, which generally has a high refractive index, helps tuning the overall refractive index of the coating within the solar spectrum. In recent years, a composite consisting of metallic nickel (Ni) NPs embedded in a ceramic layer of alumina (Al₂O₃) has been extensively explored as an interesting cermet solar absorber because noble metals possess a good thermal stability with a high antioxidation resistance.⁷,⁸ However, there is still much to improve in the properties of these materials in order to harvest the maximum amount of solar energy while maintaining a high stability at elevated temperatures.

To achieve reliable solar absorbers with a high absorptance, one approach is to modify the morphology of the Ni particles embedded in the Al₂O₃ layer. Owing to different refractive indices of different forms of NPs, Ni particles in a nanochain (NC)-like structure offer a stronger solar absorption compared to spherical Ni NPs.⁹ The morphology and structure of...
anisotropic NPs has a great deal of impact on their properties arising from their size and shape. An NC configuration consists of individual NPs attached to one another and orienting themselves in a chain-like structure. With this unique nanostructure of Ni particles dispersed in the Al₂O₃ layer, the overall solar absorption can be significantly enhanced due to multiple scatterings in which the light can be reflected back and forth within the coating, minimizing thermal emittance losses.

It is well-known that Ni is a magnetic material, and so the formation of a Ni NC structure can be induced by an external magnetic field-assisted or template-assisted method. So far, several diverse suitable methods have been reported in the literature for the synthesis of Ni NCs, including hydrothermal, electrodeposition, and wet chemical reduction. However, these methods rely on the magnetic field and/or a template for directing the growth and controlling the size and anisotropic shape of the Ni NPs. According to various well-established approaches, it was found that the magnetic field was a key factor to control the movement and orientation of magnetic Ni particles. Moreover, the presence of surfactants, such as an amine or oleic acid, is still necessary to control the reaction and they affect the particle shape, size dispersion, and stability.

On the other hand, in template-assisted methods, the removal of the template at the end of the reaction is required, which makes the process more complicated. Apart from these factors, the operating parameters in the reaction process, such as the concentration of precursors, pH, and temperature, also need to be well controlled. Among the potential morphology-controlled synthesis methods, chemical reduction has been demonstrated as an interesting and widely used method due to its ease of reaction control and high yield of product. Nevertheless, it is still a challenge to develop the synthesis of Ni NCs via chemical reduction without a template and magnetic field. Only a few studies have previously been reported.

While the template- and magnetic field-free approach can reduce the number of complicated procedures while enabling control of the morphology and structure of the formed Ni NPs, there is little detail on the formation of Ni NCs. Hence, in this work, an investigation of various parameters associated with the chemical reduction method was performed. The change in morphology of the Ni NPs during the reaction was monitored in order to propose the mechanism of formation of the NC structure, which is an effective means to gain a better understanding of Ni NC growth. This information will enable the tailoring of the morphology and structure of the Ni NCs used for embedding in the Al₂O₃ thin layer and so fine-tune their properties to serve in cermet-based solar absorber coatings.

2. RESULTS AND DISCUSSION

2.1. Formation of Ni NCs. In this work, Ni NCs were prepared without a template or magnetic field via chemical reduction for 1 h at different NaOH: NiCl₂ molar ratios in the range of 4–20 with their morphologies, as observed by SEM, shown in Figure 1. At a molar ratio of 4, the assembly of spherical Ni NPs into a chain-like morphology was observed with an average diameter and length of approximately 340 ± 70 nm and 1.57 ± 0.79 μm, respectively. Increasing the NaOH: NiCl₂ molar ratio up to 8 resulted in Ni NCs with slightly smaller diameter of Ni particles but a longer chain length. However, at NaOH: NiCl₂ molar ratios above 8, the average diameter of the Ni NPs increased to 540 ± 100 nm and the chains became shorter, and at a molar ratio of 20, the chains completely collapsed into globules. Thus, the formation of Ni NCs was significantly influenced by the NaOH: NiCl₂ molar ratio.

To determine the mechanism of Ni NC formation, HRTEM was used to characterize the morphology of the Ni NPs derived at different reaction times. First, Ni samples prepared from a NaOH: NiCl₂ molar ratio of 8 after (a) 10, (b) 20 min. The particles were almost spherical in shape and had a diameter of about 300 nm. By 20 min, the particles had started to grow larger with an average diameter of 450 nm and some particles came in contact with each other and formed a chain-like morphology, as seen in Figure 2b. With reaction times over 20 min, a larger number of particles was observed and the number of particle-particle interactions increased.

Figure 1. Representative SEM micrographs of synthesized Ni NPs prepared from a NaOH: NiCl₂ molar ratio of (a) 4, (b) 6, (c) 8, (d) 10, (e) 12, and (f) 20 for 1 h.

Figure 2. Representative HRTEM micrographs of Ni NPs and NCs prepared from a NaOH: NiCl₂ molar ratio of 8 after (a) 10, (b) 20 min. (inset shows the arrangement of Ni particles into an NC), (c) 30, (d) 40, (e) 50, and (f) 60 min (inset shows a cone-shaped structure on the Ni particles at the end of some NCs in a relatively higher magnification) of reaction time.
chains of Ni became longer as a result of continuous contact of near-globular individual particles in an axial direction, as shown in Figure 2c–f. Interestingly, it can be seen in the inset of Figure 2f that the spherical particles located at the end of some chains had cone-shaped structures on the surface. The formation of a sea-urchin-like Ni nanostructure obtained from a wet chemical method was previously reported and found to rely on the addition sequence of hydrazine and NaOH. The sea-urchin-like Ni particles were obtained by adding hydrazine prior to NaOH, while vice versa yielded spherical-shaped ones. Therefore, in this present work, it was likely to observe this unique morphology in some parts of the sample.

While the reaction time was associated with the growth of Ni NPs, the NaOH:NiCl₂ molar ratio could also play an important role in the obtained morphology of the Ni samples. Hence, Ni samples prepared from a NaOH:NiCl₂ molar ratio of 20 at different reaction times were also investigated in comparison with those prepared at a molar ratio of 8 (demonstrated earlier). As shown in Figure 3, it was obvious that individual Ni particles were aggregated into NCs from 10 min of reaction time, as seen in Figure 2c–f. An increasing number of Ni NPs and NCs were observed at longer reaction times, as seen in Figure 3a. An increasing number of Ni NPs and NCs were observed at longer reaction times. However, the Ni NCs began to collapse and fold on the surface of many of Ni particles. It was evident from this study that the concentration of NaOH relative to NiCl₂ is an important factor in controlling the reduction reaction and morphology of Ni. To clarify the formation mechanism of Ni NCs, according to the chemical reduction reaction expressed in eq 1:

\[
2\text{Ni}^{2+} + 2\text{NH}_2\text{H}_4 + 4\text{OH}^- \rightarrow 2\text{Ni} + 2\text{N}_2 + 4\text{H}_2\text{O} \tag{1}
\]

The Ni²⁺ ions were reduced by hydrazine, which acts as a reductant, while the NaOH that was added to adjust the pH of the solution also acted as a catalyst for the reduction reaction. Initially, Ni²⁺ formed a complex with hydrazine. Once NaOH was added, the Ni-hydrazone complex transformed into nickel hydroxide \( \text{[Ni(OH)₂]} \) followed by nucleation of Ni. Thus, increasing the concentration of NaOH led to a larger number of Ni(OH)₂ nuclei and thereby smaller Ni particle sizes as a result of the lower Gibbs free energy, as previously reported. Not only did NaOH induce the reduction reaction to be faster, the glycol functional group (–OH) from EG also formed on the surface of the Ni NPs as a protective layer and restricted the particle size, resulting in a higher agglomeration of particles and thereby preventing the formation of the NC structure. For this reason, Ni samples derived from a NaOH:NiCl₂ molar ratio of 20 tended to form globular-shaped particles and disordered clusters at the end of reaction, as demonstrated in Figures 3f and 3g.

In explanation, at the early reaction stage, the natural magnetism of Ni particles was dominant over agglomeration and so they formed NCs. In the later reaction stages, when the glycol functional groups formed on the Ni particle surfaces, agglomeration of particles was more pronounced with respect to the magnetic dipole–dipole interaction, thereby possibly isolating particles. On the other hand, when the concentration of NaOH with respect to NiCl₂ was decreased, the reduction process was significantly slower, allowing individual particles to grow under the control of the glycol functional groups forming on particle surfaces. Simultaneously, particles were attracted to each other as a result of the intrinsic magnetic characteristic of Ni and so subsequently formed the Ni NC structure. Larger particles resulted in a stronger magnetic interaction as well as a lower surface area, and so a lower degree of particle agglomeration was observed. Thus, the Ni NC conformation was still maintained under magnetization at the later stages of the reaction. From the results, a NaOH:NiCl₂ molar ratio of 8 was, therefore, selected as the optimal condition for the transformation of Ni NPs into NCs that remained stable through to the end of the 1 h reaction, as seen in Figures 2c and 3f.

A further study was performed by replacing NaOH with ammonia solution (\( \text{NH}_4\text{OH} \)) using the same hydroxyl (\( \text{OH}^- \)):NiCl₂ molar ratio of 8. As shown in Figure 4a, indicating that the \( \text{OH}^- \) group was likely to be the key factor controlling the reduction reaction and morphology of Ni. To summarize, we proposed the formation mechanism of Ni NCs based on their preparation at a NaOH:NiCl₂ molar ratio of 8. As soon as NaOH was added into the solution, nucleation of Ni occurred, as in eq 1. The nuclei continued to grow until

![Figure 3. Representative HRTEM micrographs of Ni NPs and NCs prepared from a NaOH:NiCl₂ molar ratio of 20 for (a) 10, (b) 20, (c) 30, (d) 40, (e) 50, and (f) 60 min reaction time.](attachment:image1.png)

![Figure 4. (a) Representative SEM micrograph of the synthesized Ni NPs and NCs prepared from a NaOH:NiCl₂ molar ratio of 8 for 1 h and (b) a schematic representation of the Ni NC formation.](attachment:image2.png)
they reached a critical size. At this stage, each stable particle exhibited a magnetism behavior, and so they attracted each other and aligned along the magnetic induction line forming Ni NCs even in the absence of an external magnetic field. The NC conformation was maintained throughout to the end of the 1 h reaction. Furthermore, association of the functional glycol groups on the particle surfaces formed like an envelope for each particle in the chain, as shown in the squared area in Figure 4b, allowing flexibility of the NCs and preserving their structure.25

Next, the synthesized Ni NCs were confirmed by XRD. The typical XRD patterns of the samples obtained from NaOH:NiCl2 molar ratios of 4, 8, 10, and 20 are shown in Figure 5. The diffraction peaks at 44.4, 51.8, 76.3, and 92.9° can be assigned to the planes of (111), (200), (220), and (311), respectively, corresponding to the face-centered cubic structure of the Ni phase. No additional diffraction peaks from impurities of Ni oxide or hydroxide compounds were detected, indicating that the Ni NCs were high in purity. It was observed that the peak widths of each plane from the samples prepared from different NaOH:NiCl2 molar ratios were variable, which was attributed to the different average particle sizes and shapes of the Ni samples.

2.2. Effects of Morphology on Solar Absorbing Properties. To fabricate the Ni–Al2O3 cermet solar absorbing coatings, Ni particles prepared from different NaOH:NiCl2 molar ratios were dispersed in an Al2O3 suspension and deposited on the respective SS substrate. The SEM surface images of the samples (Figure 6) revealed full coverage of the SS and a crack-free film in which the Ni particles appeared to embed in and on the surface of the Al2O3 layer. For the coatings composed of Ni particles prepared from the lower NaOH:NiCl2 molar ratios, a cluster of Ni NCs was spread on the surface, while those prepared from higher molar ratios displayed globular particles and shorter chains on the surface. In addition, in order to determine the distribution of Ni NCs in the Al2O3 layer, cross-sectional EDS element mapping analysis was performed for the samples with corresponding preparation conditions, as shown in the bottom images in Figure 6. It can be seen that at a lower NaOH:NiCl2 molar ratio, the embedded Ni particles were distributed uniformly throughout the Al2O3 layer, while at higher molar ratios (above 12), the Ni particles aggregated into large clusters, resulting in a low dispersibility of Ni in the coatings, especially for Ni particles prepared from a molar ratio of 20. Table 1 displays the average atomic compositions of the SS, Al2O3 on SS and Ni–Al2O3 on SS, as measured by the EDXRF analysis to confirm the presence of the Ni–Al2O3 cermet coating on the substrate. It was noted that five different areas on the samples were measured to determine the average values. The sample revealed Al and O elements, indicating the presence of the Al2O3 film and Ni, which was mainly detected from the synthesized Ni particles but also a minor portion from the metallic nature of the SS substrate.

Figure 7 shows the measured spectral reflectance (R) of the Ni–Al2O3 cermet solar absorber derived from Ni particle synthesis under different NaOH:NiCl2 molar ratios, in comparison with the AM 1.5 solar spectrum, over wavelengths from the UV–vis–NIR regions (300–2500 nm). All the samples exhibited a low R value (below 50%) over the whole wavelength range and R increased with increasing wavelength. With increasing NaOH:NiCl2 molar ratios up to 8, the spectral R decreased to a minimum value (dashed line in Figure 7). A lower reflectance was observed from the samples with a Ni NC structure (synthesized from a NaOH:NiCl2 molar ratio of 6 or 8), whereas the shorter Ni NCs synthesized at a molar ratio of 4 and the spherical-like Ni NPs synthesized at molar ratios of 12 and 20 exhibited a higher R. The solar absorptances (α) of all the samples with approximately the same film thickness were calculated using eq 2 and are summarized in Table 2. The cermet coating consisting of Ni NCs prepared from a NaOH:NiCl2 molar ratio of 8 showed...
the Al₂O₃ layer (green color). The spectral reflectance (R) of the Ni–Al₂O₃ cermet solar absorber prepared from different NaOH: NiCl₂ molar ratios, in comparison with the solar spectrum at AM 1.5 in the wavelength range of UV–vis–NIR regions.

![Image](https://dx.doi.org/10.1021/acsomega.0c03077)

Figure 7. Representative spectral reflectance (R) of the Ni–Al₂O₃ cermet solar absorber prepared from different NaOH: NiCl₂ molar ratios, in comparison with the solar spectrum at AM 1.5 in the wavelength range of UV–vis–NIR regions.

![Image](https://dx.doi.org/10.1021/acsomega.0c03077)

Table 2. Solar Absorptance of the Ni–Al₂O₃ Samples Prepared from Different NaOH: NiCl₂ Molar Ratios

| NaOH: NiCl₂ molar ratio | solar absorptance (α) | film thickness (μm) |
|-------------------------|-----------------------|---------------------|
| 4                       | 0.715 ± 0.017         | 2.73 ± 0.15         |
| 6                       | 0.775 ± 0.013         | 2.80 ± 0.12         |
| 8                       | 0.816 ± 0.019         | 2.72 ± 0.21         |
| 10                      | 0.774 ± 0.003         | 2.91 ± 0.11         |
| 12                      | 0.744 ± 0.002         | 2.54 ± 0.35         |
| 20                      | 0.701 ± 0.056         | 2.94 ± 0.12         |

aData are shown as the mean ± 1 SD, derived from three independent repeats.

the highest performance with a 0.82 solar absorptance. Compared to a cermet coating with embedded spherical Ni NPs prepared from a molar ratio of 20, a 16.4% increase in solar absorptance was observed with the Ni NCs. This absorption phenomenon can be explained by the contribution of superior light trapping enhancement of the NCs by multi-scattering the light and increasing the path length of light among the NCs, which may increase the overall absorption.

2.3. Effects of the Ni Content in Cermet Films. Not only did the morphology impact on the solar absorption property but the amount of Ni NCs in the Al₂O₃ layer also played an important role in tailoring the solar absorptance of the cermet coatings. Figure 8 shows the cross-sectional SEM images of Ni–Al₂O₃ cermet coatings prepared from Ni NC (prepared from a molar ratio of 8) contents ranging from 10–200 mg in the Al₂O₃ layer where a higher Ni content led to a higher density of particles in the film. The analysis of the cross-sectional EDS mapping was also performed in order to indicate the presence of Ni NCs distributed in the Al₂O₃ layer, as shown in the bottom images in Figure 8. The red pigment particles revealed the concentration of Ni NCs embedded in the Al₂O₃ layer (green color). The spectral reflectance (R) and calculated solar absorptance (α) of the Ni–Al₂O₃ cermet solar absorbers with different Ni NC contents are shown in Figure 9 and Table 3, respectively. The reflectance of the sample decreased with increasing Ni NC contents, resulting in a higher solar absorptance. The present result is consistent with the result obtained by Li et al.²⁶ It was found that 0.2 g of Ni NCs in the Al₂O₃ layer demonstrated the highest solar absorptance (0.91), but further increasing the Ni content above 0.2 g led to precipitation of excess Ni particles in the Al₂O₃ suspension (data not shown). Not only the morphology of Ni NPs and the content of Ni NCs dispersed in Al₂O₃ films have an impact on the solar absorbing property but the film thickness of the Ni–Al₂O₃ layer is also another important factor affecting the solar absorptance. However, the detailed analysis of this factor is beyond the scope of this study. Hence, it is suggested that the optimization approach using design of experiments, which have been reported elsewhere,²⁷ is taken into account in the future work.

![Image](https://dx.doi.org/10.1021/acsomega.0c03077)

Figure 8. Representative cross-sectional (upper) SEM micrographs and (lower) corresponding cross-sectional EDXRF elemental mapping of Ni–Al₂O₃ cermet absorber films (Ni = red, Al₂O₃ = green) with a Ni content of (a) 0.01, (b) 0.02, (c) 0.05, (d) 0.1, and (e) 0.2 g in the Al₂O₃ layer (Ni NCs were prepared from a NaOH: NiCl₂ molar ratio of 8).

![Image](https://dx.doi.org/10.1021/acsomega.0c03077)

Figure 9. Representative spectral reflectance (R) of the Ni–Al₂O₃ cermet solar absorber prepared from different contents of Ni NCs (prepared from a NaOH: NiCl₂ molar ratio of 8) in the Al₂O₃ layer.

Table 3. Solar Absorptance of the Ni–Al₂O₃ samples with Different Contents of Ni NCs

| Ni content (g) | solar absorptance (α) | film thickness (μm) |
|---------------|-----------------------|---------------------|
| 0.01          | 0.664 ± 0.022         | 2.66 ± 0.22         |
| 0.02          | 0.688 ± 0.010         | 2.56 ± 0.28         |
| 0.05          | 0.816 ± 0.019         | 2.72 ± 0.13         |
| 0.1           | 0.862 ± 0.022         | 2.78 ± 0.19         |
| 0.2           | 0.910 ± 0.009         | 2.65 ± 0.24         |

²Ni samples were prepared from a NaOH: NiCl₂ molar ratio of 8. Data are shown as the mean ± 1 SD, derived from three independent repeats.
Based on the investigation in this work, Al₂O₃-based coatings consisting of Ni NCs embedded in the Al₂O₃ layer display a promising solar absorbing property, which is as high as other cermet coatings. Including a top anti-reflectance layer, this specific coating can exhibit high absorptance and good thermal stability in air at high temperatures, which shows a potential for mid- and high-temperature solar thermal applications. Together with the simple and low-cost deposition process of rapid convective deposition employed in this work, Ni–Al₂O₃ cermet coatings can be prepared with cost effectiveness due to low energy consumption, low material consumption, low material wastage, and potential for large-scale production.

3. CONCLUSIONS

The chemical reduction method was successfully implemented for the synthesis of highly uniform Ni NCs without the assistance of a template or external magnetic field. The concentration of NaOH with respect to NiCl₂ was a key factor in controlling the reaction and tailoring the morphology of the obtained Ni NPs. The formation of Ni NCs was attributed to the intrinsic magnetic property of Ni with the magnetic dipole interaction overcoming the particle growth during the reaction process, leading to the orientation of Ni NPs into a chain-like configuration. The mechanism of the dependence on the NaOH:NiCl₂ molar ratio on the Ni NC growth was proposed in order to find the optimum condition for the synthesis of uniform Ni NCs. With its unique morphology, different sizes, shapes, and configurations of Ni NPs embedded in the Al₂O₃ films as cermet coatings were compared in terms of their solar absorbing performance. The coating with highly uniform Ni NCs in the Al₂O₃ exhibited a superior overall solar absorptance, presumably due to the multiple light scatterings, compared to those with globular Ni NPs. Moreover, increasing the Ni NC contents in the Al₂O₃ layer also resulted in an enhanced solar absorptance. Thus, Ni–Al₂O₃ coatings using Ni NCs can be used as a promising material candidate for cermet-based solar absorbers.

4. EXPERIMENTAL SECTION

4.1. Synthesis of Ni NCs. All chemicals, including nickel chloride (NiCl₂·6H₂O), hydrazine (N₂H₄·H₂O), ethylene glycol (EG), sodium hydroxide (NaOH), ethanol, acetone, nitric acid (HNO₃), aluminum isopropoxide, and hydrochloric acid (HCl) were of analytical grade and were used as received without further purification. Ni NCs were synthesized via chemical reduction without a stabilizer. For this, 0.045 M NiCl₂·6H₂O and 0.9 M hydrazine were dissolved in EG, which acts as the solvent. Then, 0.18–0.90 M NaOH solution was added to obtain NaOH:NiCl₂ molar ratios ranging from 4–20. The solution was stirred constantly in a capped bottle at 60 °C for 1 h and subsequently cooled down to room temperature. The initial transparent green solution slowly turned into a black colloidal suspension, indicating the formation of Ni particles. The obtained Ni particles were then repeatedly washed with acetone and ethanol three times to remove impurities and dried in an oven at 80 °C for 1 h.

4.2. Fabrication of Ni–Al₂O₃ Cermet Films. The colloidal Al₂O₃ suspension was prepared by a sol–gel method under an acidic condition. First, 0.18 M aluminum isopropoxide in a 1:1 (v/v) deionized water:ethanol mixture was heated in a closed container at 80 °C for 1 h with vigorous stirring. The solution was adjusted to pH 2.5 by addition of an appropriate amount of HCl and maintained with stirring at 90 °C for another 2 h in an open bottle. Next, 0.01–0.2 g of Ni particles (section 2.1) was added into 2 mL of this Al₂O₃ suspension in order to prepare Ni–Al₂O₃ cermet suspension. A 304-type stainless-steel (SS) sheet, used as the substrate, was etched with 1.4 M HNO₃ solution at room temperature for 10 min and ultrasonically cleaned in acetone at 60 °C for another 30 min. A total of 20 μL of Ni–Al₂O₃ suspension was deposited on the SS substrate by the rapid convective deposition (RCD) method at a speed of 10,000 μm/s. The coated film was then dried at 80 °C for 1 min to remove the solvent and subsequently annealed in a nitrogen (N₂) atmosphere at 400 °C for 1 h. The RCD is an alternative efficient solution-based deposition method used to fabricate a thin film from a colloidal solution. In the RCD method, the organization of particles into a thin layer on the substrate is driven by the evaporation flow and/or viscous drag force when the solution is dragged by a deposition blade across the substrate, as shown schematically in Figure 10. Various morphologies of the films can be obtained under the controlled deposition parameters.

4.3. Characterization. Ni NPs prepared from several batches with the same condition were collected. The morphology and chemical composition of Ni NPs and Ni–
Al₂O₃ cermet films from each batch were characterized and confirmed reproducibility using scanning electron microscopy (SEM) coupled with the X-ray analysis (EDS), high-resolution transmission electron microscopy (HRTEM; JEOL-2100 Plus operated at 200 kV), and energy-dispersive X-ray fluorescence (EDXRF), respectively. The phases of the samples were determined by X-ray diffraction (XRD). The reflectance (R) of the Ni–Al₂O₃ cermet films was measured using a UV–vis–NIR spectrophotometer (Agilent technologies, Cary 5000) over a wavelength range of 300–2500 nm with an integrating sphere. The solar absorptance was calculated from eq 2:

\[
\alpha_s = \frac{\int_{\lambda_1}^{\lambda_2} I_s(\lambda)(1 - R(\lambda))d\lambda}{\int_{\lambda_1}^{\lambda_2} I_s(\lambda)d\lambda}
\]

where \(I_s(\lambda)\) is the solar spectral radiation of air mass 1.5 from standard ASTM G173 and \(R(\lambda)\) is the measured reflectance at a specific wavelength \(\lambda\) (wavelength interval \(\lambda_1\) to \(\lambda_2\) = 300–2500 nm).

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Notes
The authors declare no competing financial interest.

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