Effect of carbon nano-tubes and dispersions of SiC and Al₂O₃ on the mechanical and physical properties of copper-nickel alloy

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Abstract

This paper investigates the mechanical and physical properties of Cu-Ni alloy (at 50-50 wt. %), mixed with different reinforcement materials such as carbon nanotubes CNT (0.5–2 wt. %) as nano particles, Al₂O₃ (1–4 wt. %) and SiC (1–4 wt. %) as microparticles. The obtained composite specimens characteristics were evaluated such as microstructure, density, electrical conductivity, thermal conductivity, hardness, and compression properties to determine the suitable reinforcement percentage that has the best physical and mechanical properties. The micron-sized Al₂O₃ and SiC and nano-sized CNT were added to enhance the mechanical and physical properties of the composite. The hardness and compression yield stress of Cu-Ni base composites have shown the most positive enhancement values of up to 135 % and 136 % of the matrix, respectively.

Keywords: Materials science, Mechanical engineering
1. Introduction

Mechanical alloying is a manufacturing process that merges several hardening mechanisms instantaneously, which is called mechanical milling when applied to pure materials. It is known that the Cu-Ni alloys have a good combination of physical and mechanical properties. They can withstand high stress loading, as well as high temperatures. Also, they have desirable properties such as electrical and thermal conductivities together with corrosion resistance, which make copper-nickel alloys standout options in a lot of industrial sectors [1, 2, 3]. For copper-based alloys, the most important alloying elements used are Si, Sn, Al, Zn and Ni. Those elements, except for Ni, have limited solubility in the solid form (8, 9, 19 and 37%, at maximum), respectively [1, 4]. Nickel has a positive effect on the mechanical and physical properties of Cu-Ni alloys in terms of liquidus and solidus temperatures and corrosion resistance.

It has been provided in many research reports that the matrix can be enhanced by incorporating it with different types of reinforcement with various volume fractions. CNTs are ideal reinforcements for advanced composite materials for many engineering applications. They are categorized by a lot of features involving a tensile strength of over 150 GPa, Young’s modulus of more than 1 TPa and thermal conductivity of up to 6000 W/(m·K) [5, 6, 7]. However, due to some obstacles such as difficulty of obtaining good homogenous dispersion of CNTs inside metal matrices [8], the difficulty of bonding, reactions with the metal matrices, and damage of CNTs during processing, widening their applications still needs a lot of efforts [9, 10, 11].

In this regard, the current research work focuses on the dispersion of CNTs with Cu-Ni mechanically alloyed matrix, which was the main subject of some previous reports [12, 13, 14]. Previously, some researches were interested in improving the mechanical properties (hardness, compression etc.) [8, 15], thermal and electrical conductivities of Cu-Ni composites [14, 16, 17]. Moreover, some studies focused on powder metallurgy technique for processing ceramic powder (Al₂O₃ and SiC) as reinforcements [18, 19, 20].

C. Kim et.al. studied the nickel-coated single wall CNT as a reinforcement with copper matrix composites [19]. The composite specimens were made by hot-pressing. The mechanical and tribological properties of obtained specimens slightly improved compared to those of pure copper and copper—nickel specimens. However, adding carbon nanotubes did not improve electrical and thermal conductivities compared to those of the sintered copper—nickel specimen with same composition. Besides, P. Rojas et.al. showed that the consolidated 50%Cu-50%Ni and 60%Cu-40%Ni alloys obtained by powder metallurgy illustrated better behavior in terms of corrosion resistance compared to copper and nickel samples [20]. The process conditions of sintering temperature and compaction pressure values used were 300 °C and 900 MPa with 5 hours of milling.
On the other hand, S. Mostafa et.al. investigated the densification and compression properties of Cu–20% coated SiC, Cu–20% SiC, Cu–20% coated Al2O3, and Cu–20% Al2O3 composites [17]. The Cu-composites were made by mixing uncoated powders of SiC sintered at constant temperature of 900 °C. The Cu matrix Ni coated reinforced composites showed higher relative density and lower porosity content than the uncoated composites due to the good bonding between the reinforcements and the Cu-matrix. Compression strengths of coated reinforcement powders-containing composites are higher than those of uncoated ones.

The current work uses the powder metallurgy technique for the addition of CNT and ceramic powder (Al2O3 and SiC) with microns grain sizes as reinforcements for Cu-Ni mechanical alloy at different percentages optimized to achieve the best physical and mechanical properties. Besides, the obtained specimens were investigated with various mechanical tests as well as microstructural investigations (optical and Scanning Electron Microscopy (SEM)), density, electrical conductivity, thermal conductivity, hardness and compression strength.

2. Experimental

In this research, powder metallurgy technique was used to prepare the composite samples which consist of copper-nickel alloy strengthened by various types of reinforcements. They included multi-walled carbon nano-tubes (MWCNTs), Al2O3 and SiC ceramic powders. MWCNTs were bought from FiberMax Composites company, Greece (with length: 1–25 μm, average diameter: 10–40 nm, specific surface area: 150–250 m²/g and purity by weight: 99% min). CNTs were used as reinforcements with different percentages (from 0.5-2 wt. %.) added to copper-nickel alloy. Both Al2O3 (60 microns particle size) and SiC powders (10 microns particle size) were also used with percentages from 1-4 wt. %. The alloy (50-50 wt. %) was prepared using mechanical alloying of 2–3 microns grain size for pure copper and 1 micron grain size for nickel powder mixed using high energy milling in a SPEX 800 rpm mixer/mill with a ball-to-powder ratio of 10:1. The milling time was set at 20 hours to have a homogeneous mixing between copper and nickel powders to form the matrix of the composite.

It has been provided in many previous reports that mixing Cu and Ni powders with carbon nano-tubes, as well as ceramic powders, is an obstacle as they are easily separated from each other [11]. So, this paper seeks to provide an effective way to form a mixture using chemical dispersant as cyclohexane-C₆H₁₂ to form an appropriate environment for mixing, and paraffin wax as a lubricant during compaction to decrease friction with concentrations 20 wt. % and 0.5 wt. %, respectively. The mixing process was performed by a stainless steel container in a SPEX mixer/mill at 800 rpm for one hour. After mixing, the mixture was dried in an oven for one hour at
about 100 °C that allows to melt the wax and to let it mix well with Cu-Ni powder and CNT mixture. Then, the mixture was compressed in a rectangular die made from Cr-Mo alloy steel (DIN W302). The die cavity had a rectangular cross-section with 8 × 6 mm² area with 15 mm height. The hydraulic uni-axial press machine was used at a compaction pressure of 600 MPa to attain the compacted specimens. The sintering process was performed in a vacuum furnace at 1050 °C for 2 hours. The heating rate was adjusted at 4 °C/min till 250 °C where the temperature was kept constant for 30 min to complete the debinding stage. Then, the heating rate was increased to 6 °C/min till the maximum. Then the specimens were cooled in the furnace. Fig. 1 illustrates the details of the whole powder metallurgy process.

The sintered samples were investigated under various types of tests. For microstructure examination, the specimens were prepared using standard grinding with 120, 220, 400, 600, 800, 1000, 1200, 2000 and 3000 grit SiC papers, and then they were polished with 6 micron diamond paste. Optical microscope (type Axioplan) was used to demonstrate microstructure features using digital camera type Cannon PC1049 fitted with ZIESS lenses. The microstructure of the polished samples was inspected by field emission scanning electron microscope (FESEM; QUANTA-FEG250), Holland. Also, the actual density of the sintered composites was calculated using Archimedes rule, using water as a floating liquid. The sintered specimens were weighed in air and in distilled water and their actual densities ($\rho_{act.}$) were determined according to the following equation:-
\[ \rho_{\text{act.}} = \frac{W_a}{W_a - W_w} \]  
(1)

Where \( W_a \) and \( W_w \) are the masses of the sample in air and water, respectively. The theoretical density (\( \rho_{\text{th}} \)) for the investigated composite was determined according to the following equation:-

\[ \rho_{\text{th}} = (V_M \times \rho_M) + (V_R \times \rho_R) \]  
(2)

Where \( V_M \) and \( \rho_M \) are the volume fraction and density of the matrix while \( V_R \) and \( \rho_R \) are the volume fraction and density of the reinforcement. The degree of porosity of the sintered compacts was determined according to the following equation:-

\[ \text{Porosity \%} = 1 - \frac{\rho_{\text{act.}}}{\rho_{\text{th}}} = \left( \frac{\rho_{\text{th}} - \rho_{\text{act.}}}{\rho_{\text{th}}} \right) \]  
(3)

The electrical conductivity was estimated using a four-terminal ohmmeter for high accuracy. One pair of terminals measures voltage, while the other pair measures current. This permits the ohmmeter to ignore the resistance of the second pair of terminals. Then, the resistance of the specimen was recorded using the ohmmeter.

\[ \sigma = \frac{L}{AR} \]  
(4)

Where:

- \( \sigma \): electrical conductivity (S/m).
- \( L \): the distance between the ohmmeter terminals.
- \( A \): the area of the surface that the ohmmeter is measuring current across.
- \( R \): electrical resistance of the specimen.

The thermal conductivity was estimated from the electrical conductivity using Wiedemann-Franz law

\[ K = LT\sigma \]  
(5)

Where:

- \( K \): thermal conductivity W/(m·K)
- \( \sigma \): electrical conductivity (S/m).
- \( L \): Lorenz number \( (2.45 \times 10^{-8} \text{ WΩk}^{-2}) \).
- \( T \): the room temperature (K).

Vickers hardness was measured at a load of 10 Kgf and the time to make an indentation was 10 seconds for all specimens. The reported Vickers hardness values of the specimens represent the average of 5 readings of each sample. Compression strength test of the investigated samples was performed using a micro-computer-controlled uniaxial universal testing machine HT-9501. The samples used for compression tests...
were of a rectangular $8 \times 8$ mm$^2$ cross-section and a height of 15mm. The applied cross-head speed of universal test machine used in this study was 2 mm/min. The test was conducted at room temperature.

### 3. Results and discussion

This section illustrates and discusses the physical and mechanical properties of the sintered composites such as hardness, mechanical properties, thermal conductivity, electrical conductivity, and the density with physical and mechanical properties measured value as shown in Table 1. Fig. 2-a illustrates the microstructure of the copper-nickel alloy (50-50 wt. %). It is noted that the matrix alloy is almost free from holes and voids due to an excellent homogenous distribution of both copper and nickel. Also, the nickel grain size is smaller than the copper grain size which permits them to occupy the copper particles spaces.

Fig. 2 (b, c) shows the microstructure of sintered composite of copper-nickel alloy with 0.5% and 1.5% CNT, respectively. It is clear that while increasing CNT percentage in copper-nickel alloy matrix, its homogenous distribution inside the specimens has been kept unharmed. Also, it can be seen that CNTs are making a high bonding between copper and nickel grains that will be important factor for enhancing both the physical and mechanical properties. Light areas stand for Cu-Ni alloy matrix and dark grey and cornered shapes represent the reinforcement component CNT particles and voids. The voids have been formed as a consequence of the drawbacks of powder metallurgy process.

#### Table 1. Physical and Mechanical properties measured value.

| Alloy        | Relative Density | Electrical conductivity (S/m) $10^6$ | thermal conductivity (W/m K) | Vickers hardness (kgf/mm$^2$) | Compression Yield stress (MPa) |
|--------------|------------------|-------------------------------------|-----------------------------|-------------------------------|-------------------------------|
| Cu-Ni        | 0.764            | 2.00162                             | 14.36862011                 | 34.326                        | 139.588                       |
| Cu-Ni + 0.5% CNT | 0.726           | 1.78233                             | 12.79444196                 | 32.36                         | 125.46202                    |
| Cu-Ni + 1% CNT | 0.658           | 1.93322                             | 13.87761306                 | 23.8919                       | 79.6308                      |
| Cu-Ni + 1.5% CNT | 0.587           | 2.06704                             | 14.83821764                 | 18.112                        | 50.90986                     |
| Cu-Ni + 2% CNT | 0.529           | 1.71680                             | 12.32402829                 | 14.145                        | 152.9376                     |
| Cu-Ni + 1% Al$_2$O$_3$ | 0.780     | 1.46973                             | 10.5049183                  | 43.8911                       | 220.7506                     |
| Cu-Ni + 2% Al$_2$O$_3$ | 0.767     | 1.66208                             | 11.93121935                 | 47.0201                       | 220.7506                     |
| Cu-Ni + 3% Al$_2$O$_3$ | 0.766     | 1.55158                             | 11.13803507                 | 49.188                        | 250.756                      |
| Cu-Ni + 4% Al$_2$O$_3$ | 0.752     | 1.27573                             | 9.157853266                 | 53.272                        | 278.1438                     |
| Cu-Ni + 1% SiC  | 0.782           | 1.25517                             | 9.01022593                  | 54.935                        | 194.2502                     |
| Cu-Ni + 2% SiC  | 0.764           | 2.45270                             | 17.60673772                 | 56.9127                       | 201.1152                     |
| Cu-Ni + 3% SiC  | 0.744           | 3.43138                             | 24.63216111                 | 65.521                        | 233.92                       |
| Cu-Ni + 4% SiC  | 0.731           | 1.87811                             | 13.48201385                 | 80.486                        | 329.3854                     |

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Fig. 2. Optical micrographs of sintered Cu-Ni (50-50 Wt.%) (a), Cu-Ni/0.5 wt. % CNT (b), Cu-Ni/1.5 wt. % CNT (c), Cu-Ni/1 wt. % Al₂O₃ (d), Cu-Ni/4 wt. % Al₂O₃ (e), Cu-Ni/1 wt. % SiC (f) and Cu-Ni/4 wt. % SiC (g).
Fig. 2 (d, e) shows the microstructure of sintering copper-nickel with 1 wt. % Al₂O₃ and 4 wt. % Al₂O₃ composites. It is shown that micron-sized Al₂O₃ particles have a great effect on the optical microstructure of copper-nickel alloy composite (Cu-Ni/Al₂O₃), where the specimens have a uniform homogenous distribution with Al₂O₃ reinforcement. Before the mixing process, the Al₂O₃ particle size was bigger than that of copper. However, it can be concluded from the figure that during the mixing process, the Al₂O₃ particles have become finer with sufficient distribution. It is also clear that the Al₂O₃ agglomeration and voids increase with increasing the Al₂O₃ mass fraction. It might also be worth mentioning that grain growth has already occurred in the composite sintered samples in both images in Fig. 2 (d) and (e) in a non-homogeneous manner which is a characteristic of vacuum sintered Cu matrix composites.

Similarly, Fig. 2 (f, g) illustrates the optical microstructure of sintered copper-nickel alloy matrix composites with 1 wt. % SiC and 4 wt. % SiC. It is noticeable that the specimens have an excellent homogenous distribution because the grain size of SiC is small compared to Al₂O₃. There is a small number of SiC agglomerations because of good mixing process between Cu-Ni and SiC. Also, there are less voids which lead to good physical and mechanical properties. In both micrographs of Fig. 2 (f, g), light areas indicate Cu-Ni matrix while dark grey cornered shapes stand for the reinforcement component SiC.

Fig. 3-(a-g) illustrates the Voids and reinforcements of the copper-nickel alloy microstructure (50-50 wt. %) for different types of specimens and it have been identified through microscopy to distinguish between reinforcement and the void. And in Table 2 shows the Void volume fractions of the composites, it is showed that the matrix alloy is almost free from voids due to homogenous distribution of both copper and nickel alloy.

| Composite composition | VVF % |
|-----------------------|-------|
| Cu-Ni (50-50 Wt. %)   | 0.14  |
| Cu-Ni 0.5 %CNT        | 1.65  |
| Cu-Ni 1.5 %CNT        | 10.54 |
| Cu-Ni 1 %Al₂O₃        | 1.27  |
| Cu-Ni 4 %Al₂O₃        | 5.47  |
| Cu-Ni 1 %SiC          | 1.02  |
| Cu-Ni 4 %SiC          | 0.68  |
Fig. 4-a demonstrates the microstructure of (copper-nickel alloy material after sintering) sample observed by Scanning Electron Microscope (SEM), which clearly illustrates the diffusion bonding between copper-nickel particles as a result of sintering under vacuum atmosphere for two hours at 1050 °C. The image illustrates the un-etched surface of the specimen, where grain boundaries can be clearly observed. The surface defects that appear on the SEM image of Cu-Ni specimen denote the void content. It can be noted that the obtained alloy has an excellent homogeneity.

Fig. 4 (b, c) shows SEM images of (Cu-Ni/0.5 wt. % CNT and Cu-Ni/1.5 wt. % CNT) nano-composites after sintering. It is noticed that the specimens still have excellent homogenous distribution while increasing CNT percentage in copper-nickel alloy matrix. Also, the figure indicates that CNTs are not affecting the high bonding between copper and nickel grains that is considered to be an effective factor in enhancing the physical and mechanical properties of the composite. The CNT agglomeration increases with increasing CNT mass fraction in Cu-Ni alloy composite. Light areas stand for Cu-Ni alloy matrix while dark grey and cornered shapes present the reinforcement component CNT Particles and voids.

Fig. 4 (d, e) demonstrates the SEM micrographs of Cu-Ni/1 wt. % Al2O3 and Cu-Ni/4 wt. % Al2O3 micro-composites, respectively. It can be observed that micro size Al2O3 particles reinforced sintered sample has a great effect on SEM structure of copper-nickel alloy composite (Cu-Ni/Al2O3), where the specimens have good homogeneous dispersion of Al2O3 reinforcement. It is noted that the Al2O3 agglomeration increases with increasing the Al2O3 mass fraction. Also, the specimens have less voids and their size is very small with respect to Al2O3 agglomeration.

Fig. 4 (f, g) shows the SEM micrographs of Cu-Ni/1 wt. % SiC and Cu-Ni/4 wt. % SiC micro-composites. In the micrographs, light areas indicate Cu-Ni matrix while dark grey cornered shapes stand for the reinforcement component SiC. Particles which are homogeneously distributed in Cu-Ni matrix, generally surround the Cu-Ni particles at high percentage of SiC content. It is clear that the specimens have perfect homogenous dispersion with less number of SiC agglomerations because of the good mixing process between Cu-Ni and SiC.

The relative density of the composite prepared by powder metallurgy is the most essential parameter which greatly affects its mechanical and physical properties. Fig. 5 demonstrates the relative density of copper-nickel alloy and copper-nickel alloy composites with different types of reinforcement. It can be noted that the relative density of copper-nickel alloy with CNT specimen was significantly decreased with increasing the CNT mass fraction. Also, the relative density of copper-nickel...
alloy with SiC specimen was slightly decreased with increasing the SiC mass fraction. Moreover, the relative density of copper-nickel alloy with Al₂O₃ specimen was slightly decreased with increasing the Al₂O₃ mass fraction. It is common that with increasing reinforcement mass fraction, the porosity will be increased, while Cu-Ni/CNT composite has the least relative density due to miss-match of CNT with Cu-Ni alloy.

Fig. 6 illustrates the electrical conductivity for different types of specimens using copper-nickel (50%—50%) alloy as a main matrix which has a very low electrical conductivity. It can be noted that copper-nickel alloy with Cu-Ni/3% SiC has the best electrical conductivity compared to others specimens due to the presence of
SiC which, if decomposed, provides the matrix with Si and C that keeps the electrical conductivity at high level. Also, the (Cu-Ni/1.5% CNT) curve shown a slight improvement compared to copper-nickel matrix. This may be because the CNT has a high electrical conductivity [21, 22]. But this advantage is limited to a certain range of mass friction according to the powder metallurgy technique [23]. Moreover, the (Cu-Ni/Al2O3) have the lowest electrical conductivity compared to other specimens attaining a drop of 37%, due to Al2O3 particles size as a ceramic material with poor conductivity properties. The increase in the electrical conductivity of Cu-Ni/SiC composite may be due to the partial decomposition which occurs for the SiC particles when sintering at high temperatures leading to the presence of both Si and C, which are semi-conductors.

Fig. 7 demonstrates the thermal conductivity of the investigated composites using Copper-Nickel (50%–50%) alloy matrix as a main matrix which are estimated based on the empirical equation. Cu-Ni has a very low thermal conductivity. As it follows the electrical conductivity, it can be clear that copper-nickel alloy with (3% SiC) has the best thermal conductivity \( \sim 70\% \) higher than the matrix compared to other specimens. Moreover, the (Cu/CNT) curve at region from (1%–1.5% Wt.) mass fraction has more thermal conductivity compared to copper-nickel specimen. While Cu-Ni/Al2O3 composites have the lowest thermal conductivity compared with other reinforcement, this could be related to the high insulating properties of Al2O3 ceramic powder. The high thermal conductivity of pure copper of 305.6 W/(m.K) is severely reduced by nickel addition (50% Ni) to attain 14 W/(m.K).

The Vickers macro hardness test was carried out to investigate the apparent hardness of the specimens of Cu-Ni/CNT nano-composite, Cu-Ni/SiC and Cu-Ni/Al2O3...
micro-composite. **Fig. 8** demonstrates the Vickers hardness of different types of investigated composites averaged from 5 readings per sample. It can be noticed that the hardness of Cu-Ni/Al2O3 and Cu-Ni/SiC increased with increasing the ceramics reinforcement mass fraction and has a high value compared to Cu-Ni matrix showed a net progressive increased in macro-hardness of (∼27−55%) and (∼60−135%), respectively, but the Cu-Ni/CNT decreased with increasing the reinforcement mass fraction with a decrease (∼6−58%) with respect to the matrix. This may be because the CNT surface has limited integration with Cu-Ni alloy due to the suppression of Cu diffusion during sintering [24, 25] This trend conforms well to those previously reported as the incorporation of SiC nanoparticles improved the hardness of the Cu-Ni-W coatings because of grain refining and the increase in the number of the grain boundaries that prohibited the movement of dislocations [18].

**Fig. 9** demonstrates the compression yield strength of Cu-Ni/CNT, Cu-Ni/Al2O3 and Cu-Ni/SiC and Cu-Ni sintered powder. It can be noted that the Copper-Nickel alloy can withstand high value of compression stress compared to Cu-Ni/CNT specimen. The compression strength of Cu-Ni/CNT decreased gradually to attain 88% reduction for 2% CNT with the increase of mass fraction due to the void formation during sintering in the case of Cu-Ni/CNT composite at high CNT volume fractions. This reduces the composite strength. In case of the Cu-Ni/Al2O3, the compression strength increased with increasing the Al2O3 mass fraction, while the compression strength of Cu-Ni/SiC increased with increasing SiC mass fraction because of ceramics material properties of Al2O3 and SiC. whereas Cu-Ni/Al2O3, SiC composites showed a net increasing of (∼153−278 MPa) and (∼194−329 MPa), respectively.
4. Conclusion

In this paper the carbon nanotubes, Al₂O₃ and SiC were used as reinforcements to the copper-nickel mechanical alloy matrix, which were successfully developed through powder metallurgy. Sintering temperature at a vacuum furnace was used to produce good sintered products at 2 hours sintering time and 1050 °C. The powder particle diffusion bonding can be clearly seen in the optical microscope and SEM observations of the composites. Characterizing their microstructure, physical and mechanical properties were achieved. Practical experiments have demonstrated that the mechanical properties were improved with Al₂O₃ and SiC Micro-particles size reinforcements compared to Cu-Ni alloy, while Cu-Ni/CNT with nano-particles size sintered samples slightly worsened. In addition, the electrical and thermal conductivity increased with adding CNT and SiC reinforcements to Cu-Ni alloy matrix. Moreover, the relative density were measured and the results have shown a good enhancement with Cu-Ni/CNT and Cu-Ni/SiC.

Declarations

Author contribution statement

Samah El-Khatib, Ayman Elsayed, Amel Elhabak, Ahmed Shash: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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References

[1] E.M.H.S. Printing, Metals handbook, properties and selection: nonferrous alloys and special-purpose materials, in: ASM Handbook, 2, 1992.

[2] R. Hummel, Understanding Materials Science, History, Properties, Applications, second ed., 2004.

[3] D.C.M. Ashby, H. Shercliff, Materials Engineering, Science, Processing and Design, second ed., BH Elsevier, 2010.

[4] A.I.C. Brooks, Heat Treatment, Structure and Properties of Nonferrous Alloys, ASM, Metals Park, OH., 1984.

[5] S. Iijima, Helical microtubes of graphitic carbon, Nature 354 (1991) 56–58.

[6] R.H. Baughman, A.A. Zakhidov, W.A. De Heer, Carbon nanotubes: the route toward applications, Sci. (80-. ) 297 (5582) (2002) 787–792.

[7] E.T. Thostenson, Z. Ren, T.W. Chou, Advances in the science and technology of carbon nanotubes and their composites, Rev. Compos. Sci. Technol. 61 (13) (2001) 1899–1912.

[8] Z. Zheng, S. Zhao, S. Dong, L. Li, A. Xiao, S. Li, Preparation of nickel-copper bilayers coated on single-walled carbon nanotubes, J. Nanomater. 2015 (21) (2015) 1–8.

[9] Y. Chai, P.C. Chan, Y. Fu, Y.C. Chuang, C.Y. Liu, Electromigration studies of Cu/carbon nanotube composite interconnects using Blech structure, IEEE Electron. Device Lett. 29 (9) (2008) 1001–1003.

[10] K.T. Kim, J. Eckert, S.B. Menzel, T. Gemming, S.H. Hong, Grain refinement assisted strengthening of carbon nanotube reinforced copper matrix nanocomposites, Appl. Phys. Lett. 92 (12) (2008) 3–5.

[11] A.S. Muhsan, F. Ahmad, N.M. Mohamed, M.R. Raza, Fabrication and microstructural analysis of CNTs reinforced copper matrix nanocomposites via MIM technique, Appl. Mech. Mater. 47 (5) (2014) 613–621.
[12] J. Bian, M. Xiao, S.J. Wang, Y.X. Lu, Y.Z. Meng, Carbon nanotubes supported Cu-Ni bimetallic catalysts and their properties for the direct synthesis of dimethyl carbonate from methanol and carbon dioxide, Appl. Surf. Sci. 255 (16) (2009) 7188–7196.

[13] W. Yucheng, R. Rong, W. Fengtao, Y. Zaoshi, Preparation and characterization of Ni—Cu—P/CNTs quaternary electroless composite coating 43 (2008) 3425–3432.

[14] P. Bakhshaei, A. Ataie, H. Abdizadeh, Effect of CNT addition on the characteristics of Cu-Ni/CNT nanocomposite 3 (2013) (2014) 403–409.

[15] H. Ming, D. Peiling, Z. Yunlong, G. Jing, R. Xiaoxue, Effect of reaction temperature on carbon yield and morphology of CNTs on copper loaded nickel nanoparticles, J. Nanomater. 2016 (2016).

[16] N. Rahemi, M. Haghighi, A. Akbar, S. Allahyari, Syngas production from reforming of greenhouse gases CH 4/CO 2 over Ni—Cu/Al 2 O 3 nanocatalyst: impregnated vs. plasma-treated catalyst, Energy Convers. Manag. 84 (2014) 50–59.

[17] S. Moustafa, Z. Abdel-Hamid, Abd-Elhay, Copper matrix SiC and Al2O3 particulate composites by powder metallurgy technique, Mater. Lett. 53 (4–5) (2002) 244–249.

[18] M. Hashemi, S. Mirdamadi, H.R. Rezaie, Electrochimica Acta Effect of SiC nanoparticles on microstructure and wear behavior of Cu-Ni-W nanocrystalline coating, Electrochim. Acta 138 (2014) 224–231.

[19] C. Kim, et al., Strengthening of copper matrix composites by nickel-coated single-walled carbon nanotube reinforcements, Synth. Met. 159 (5–6) (2009) 424–429.

[20] P. Rojas, R. Vera, C. Martínez, M. Villarroel, Effect of the powder metallurgy manufacture process on the electrochemical behaviour of copper, nickel and copper- nickel alloys in hydrochloric acid 11 (2016) 4701–4711.

[21] V.N. Popov, Carbon nanotubes: properties and application, Mater. Sci. Eng. R43 (2004) 61–102.

[22] Anne-Claire Dupuis, The catalyst in CCVD of Carbon nanotubes, Rev. Prog. Mater. Sci. 50 (2005) 929–961.

[23] C. Kim, B. Lim, B. Kim, U. Shim, S. Oh, B. Sung, et al., Strengthening of copper matrix composites by nickel-coated single-walled carbon nanotube reinforcements, Synth. Met. 159 (2009) 424–429.
[24] C. Subramaniam, et al., One hundred fold increase in current carrying capacity in a carbon nanotube-copper composite, Nat. Commun. 4 (2202) (2013) 1–7.

[25] J. Shuai, L. Xiong, L. Zhu, W. Li, Enhanced strength and excellent transport properties of a superaligned carbon nanotubes reinforced copper matrix laminar composite, Compos. Part A Appl. Sci. Manuf. 88 (2016) 148–155.