



# Effect of nanowires and nanoparticles of copper on the structure and properties of the nanocomposite polymeric materials

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## ABSTRACT

**Purpose:** The main aim of this paper is to investigate the impact of nano-reinforcements in the form of Cu nanowires and Cu nanopowder on the structure and properties of polymeric composite materials

**Design/methodology/approach:** Developed in this paper of nanocomposite materials reinforced with Cu nanopowders and Cu nanowires they have shown the ability to carry an electrical charge, which was confirmed by testing resistivity and resistance to electrical breakdown

**Findings:** Research surface area of reinforce the material showed that the copper-dimensional nanowires an attractive material for the strengthening of polymeric composite materials. Because of their shape and dimensions, the formation of percolation paths necessary for electrical charge in the insulating matrix, are a better material reinforcement of copper nanopowder

**Research limitations/implications:** The phenomenon of current conduction through the polymer composite materials is an important property due to the use of these materials

**Originality/value:** The paper presents the effect of the addition of one-dimensional nanowires of copper into the insulating matrix epoxy resin allowing electrical conductivity produced in this way, polymeric materials nanocomposites

**Keywords:** Polymer nanocomposites; Cu nanoparticles; Cu nanopowder; Volume resistivity; Electrical breakdown

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## MATERIALS

### 1. Introduction

Polymeric composite materials have advantageous properties which result from the combination of the

polymeric matrix with a reinforcement allowing to obtain materials with properties similar to metals, but with much lower density. Therefore, it is widely used in automotive and aerospace industry or even electronics and many

others. A special group consists of polymeric nano-composite materials. A large number of polymeric materials as well as gains in a nanometer scale gives great possibilities for the design of composite materials. The selection of the polymeric matrix material providing load transfer on the external strengthening particles and having resistance to chemicals in the environment and material selection gain the nanometer scale allows to obtain nanocomposites with unique properties [1-5]. Good dispersing particulate reinforcement in the matrix material is an important aspect. Low add-on strengthening the range of 1-10% can significantly improve the properties of the polymeric nano-composite as compared to conventional polymeric composite materials. Because of the amount of gain multiple increase of the specific surface area, resulting in increased interaction of Van der Waals forces and electrostatic interactions increasing magnetic interactions, also the interface between the polymeric chains increases and strengthen the material, resulting in the properties of polymeric nanocomposite material [6-8].

An important step is the design of polymeric nano-composite materials. It is necessary to know the characteristics of both physical and chemical materials, as well as warp and strengthen the capabilities of their processing and bonding. Nanotechnology allows for the development of new materials already at this stage allowing for the effect on the structure and properties of polymeric nanocomposite materials. It leads to increased efficiency, new types of catalysts, reducing maintenance costs through eg. a reduction in consumption and increase of the functionality and new properties of nanocomposite materials [6,9,10-12].

Intensive development of polymeric nanocomposite materials reveals new application and shows the possibilities for obtaining properties that may be formed due to the needs of the customer associated with the particular application [13-16]. Studies in nanocomposite polymer materials require modern research techniques and devices for characterization of nanostructures and nanomaterials. That analysis allows to know the processes and phenomena occurring at the nanoscale.

The main aim of the paper is an explanation of the effect of nano-reinforcements in the form of Cu nanowires and Cu nanopowder on the structure and properties of polymeric composite materials.

## 2. Material and methodology

The selection of a suitable polymer matrix composite materials was made using multi-criteria analysis as outlined in [17-19]. In order to assess the material in

terms of its significance and impacts in the environmental adopted a universal ten-point scale of relative states, where 1 is the minimum passing grade and 10 remarkably high.

Based on the results of the analysis, as the matrix of the composite material is used, therefore, epoxy resin, trade name Epidian 5. For cross-linking of the resin triethylenetetramine (curing agent Z-1) in the proportions indicated by the manufacturer is applied. In contrast, the role of reinforcement in the resulting composite is copper powder (Cu) and nanopowder (Cunano), as well as nanowires (CuNWs). Tables 1 and 2 summarize the used materials.

Table 1.  
The materials used in the study (matrix)

Material	Manufacturer	Application
Epoxy resin (Epidian 5)	Z.Ch. „Organika-Sarzyna”, Nowa Sarzyna (Poland)	matrix
Triethylenetetramine (curing agent Z-1)	Z.Ch. „Organika-Sarzyna”, Nowa Sarzyna (Poland)	a crosslinking agent

Table 2.  
The materials used in the study (reinforcement)

Material	Manufacturer	Application
Micrometer scale Cu powder	P.P.H. „Stanlab” Sp.J., Lublin (Polnad)	reinforcement
Cu nanopowder (Wed 25 nm)	SkySpring Nanomaterials, Inc. (USA)	nanoreinforcement
Cu nanowires (Wed 150 ± 50 nm length. 5 mm min. in ethanol)	SkySpring Nanomaterials, Inc. (USA)	nanoreinforcement

The ingredients producing composites are mixed together in varying proportions. The reinforcements was selected as 3.5 and 9%, respectively mass fraction of powder, nanopowder or copper nanowires. The promising results of the basic polymer composites have expanded the scope of nanoreinforcement shares of 0.5 and 1%.

Crosslinking composite lasted for 24 hours. After this period, the material was removed from the molds. In the final step, the surface of cured samples were ground to remove the resultant meniscus. Collected samples were in the form of a disc of dimensions Ø 60 mm and thickness of 4 mm.

BET surface area measurement, Langmuir-point PPO porosity and adsorption energy powders and copper nanowires were made using a specific surface area analyzer Gemini VII 2390 using nitrogen gas (N<sub>2</sub>).

The observation of the distribution of the particles in the polymer matrix and the verification of dispersion and dispersion reinforcement in a polymeric matrix was made with a scanning electron microscope Zeiss Supra 35. The study was performed at a voltage of 20 kV and a maximum magnification of 5.000 times. For this purpose, the spectrometer EDS Link ISIS Oxford was used. Accelerating voltage during tests was 20 kV. The samples were sputtered with a thin layer of silver to improve contrast.

The high-resolution transmission electron microscope S/TEM Titan 80-300 was used to observe the morphology of both Cu nanopowder and Cu nanowires. The observations were made in the light and the darkness and the obtained diffraction confirming a crystalline structure of those materials.

The phase analysis of composites was performed by X-ray diffraction apparatus X'Pert Pro PANalytical. These studies were made in a goniometric filtered radiation using a cobalt lamp at a voltage of 40 kV and a filament current of 30 mA in the range of 5 to 120°. A measuring rate was 0.05°, and the time counts pulses 10 s.

Interfered spectroscopy in Fourier transformation (FT-IR) is on the basis of the application of electromagnetic radiation with determined wave length by oscillating particles. The study was performed on an FT-IR Spectrometer: 6700 Nicolet Thermo Scientific.

The tests were performed on the UV/VIS spectrophotometer Evolution 220 Thermo-Scientific. Spectral range from 190 to 1100 nm. The optical system is double beam monochromator type of Czerny-Turner, and has a system to focus the beam AFBG. It also has a xenon lamp.

Resistivity measurements were made on an Agilent 4339B High Resistance Meter Agilent Technologies. The study was performed in 3-electrode. Electrodes were made in accordance with the standard [20]. In the test, an electrode was made of bronze. The tests were performed at ambient temperature. Meter Agilent 4339B enables the study of resistivity in the range of 103 to 1.6·10<sup>16</sup> Ω. The measurements were performed at a voltage of 500 V, and the measurement time was 60 s. The measurements of each sample was repeated six times.

Tests were performed according to IEC 60243-1 ASTM D 149 [21]. Composite material with electrodes provided in the lower casing. The study was carried out in an ad hoc manner within a reasonably short time ramping up the voltage until the breakthrough. Above the critical

voltage, which depends on the type of material, the shape, structure, and environmental conditions (humidity, temperature), followed by sharp increase in electrical current called electrical leaks. Testing was performed using measuring coil with a bowl the oil, transformer of 110 kV and control panel FAE Zwarzpol in Warsaw. The temperature of measurements was 23 ± 2°C and a relative humidity of 50 ± 5%.

### 3. Results

Investigations of the surface of powders (micro and nanometer scales) and copper nanowires. Table 3 presents the measurement conditions specific surface area, and in table 4 the results of the measurement of surface area.

The reduction in size of copper powder to the nanometric significantly alters the surface area of the material. The greatest specific surface area of the materials tested strengthen characterized by a nano-sized copper powder, while the smallest surface area has a micrometer copper powder.

As a result of observing the morphology of copper powder in a scanning electron microscope (Fig. 1) and on the basis of PN-EN ISO 3252 [22] it found out that micrometer scale copper powder has a dendritic shape. Such a shape is conducive to a mechanical combination of epoxy resin and reinforcement.

Table 3.  
Basic conditions for measuring surface area of the reinforcing particles

	Cu [μm]	Cu [nm]	CuNWs
Gas		N <sub>2</sub>	
Pressure		0.1 MPa	
Sample weight	0.9963 g	0.4153 g	0.2217 g
The density of the sample		8.960 g/cm <sup>3</sup>	

Table 4.  
The results of measurement of the specific surface area by various methods

	Cu [μm]	Cu [nm]	CuNWs
Method BET	0.1120 m <sup>2</sup> /g	6.2157 m <sup>2</sup> /g	2.5878 m <sup>2</sup> /g
Langmuir method	0.9487 m <sup>2</sup> /g	141.0220 m <sup>2</sup> /g	36.2481 m <sup>2</sup> /g
One-point method (P/P <sub>0</sub> )	0.2194 m <sup>2</sup> /g	19.7062 m <sup>2</sup> /g	3.7058 m <sup>2</sup> /g

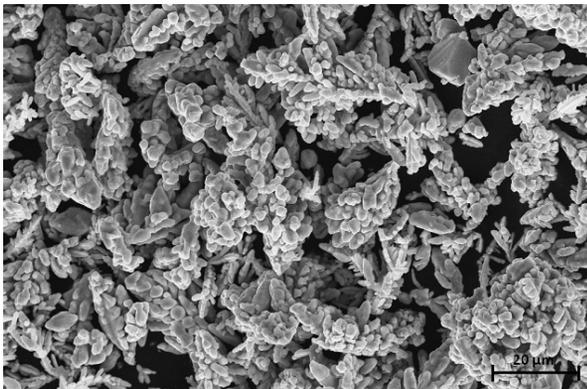


Fig. 1. The morphology of the Cu powder

On the basis of transmission electron microscopy the morphology of the copper nanowires was determined. On the basis of the image structure of the nanowires of copper (Fig. 2), it was found out that they have a similar diameter to one another. On that basis it was determined that the diameter of the nanowires of copper is less than 100 nm, wherein the average diameter of the nanowires of copper provided by the manufacturer is  $150 \pm 50$  nm. Their shape is regular. Research diffraction confirmed the crystalline construction of the copper nanowires. It was found out that copper nanowires are made of copper atoms and do not exhibit a high degree of oxidation.

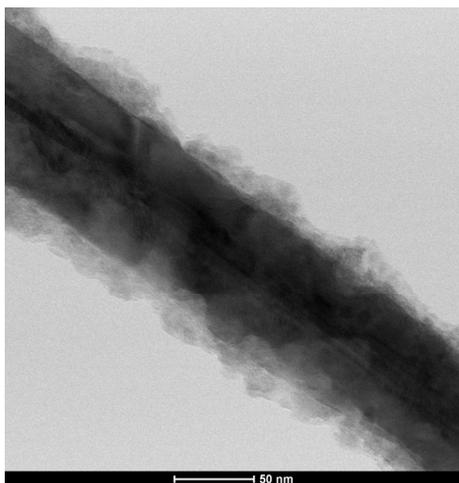


Fig. 2. The morphology of the Cu nanowires observed in the transmission electron microscope

As a result of studies with transmission electron microscopy the morphology of copper nanopowder was determined. Nanoscale particles of copper powder agglomerate very quickly. Figure 3 shows the rows of atoms that make

up the individual particles. Powder grains are surrounded by a layer of oxide, which demonstrates the oxidation of copper nanopowder.

Figures 4-6 shows the X-ray diffraction epoxy resin of composite and polymer materials. The results of X-ray pure epoxy resin confirmed the amorphous structure. Based on the results of X-ray composite polymeric materials the presence of reflections derived from the copper phase was revealed. For micrometer of copper powder and the nanowires, with the increase of their share, an increase in the intensity of reflections derived from the copper phase (Fig. 4, 6). For reinforcement in the form of copper nanopowder the presence of reflections from the phase of  $\text{Cu}_2\text{O}$  was revealed. It demonstrates the oxidation of copper nanopowder.

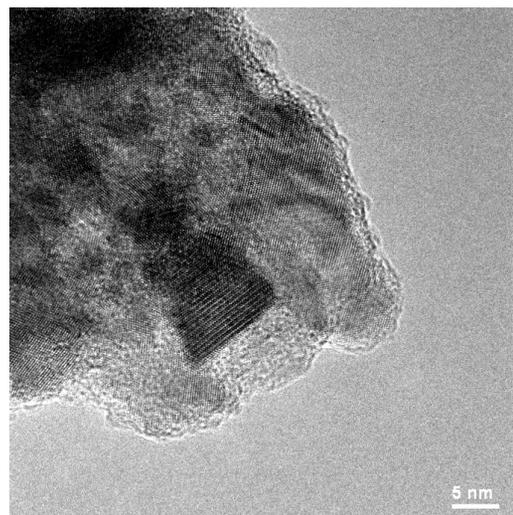


Fig. 3. The morphology of Cu nano powder observed in the transmission electron microscope

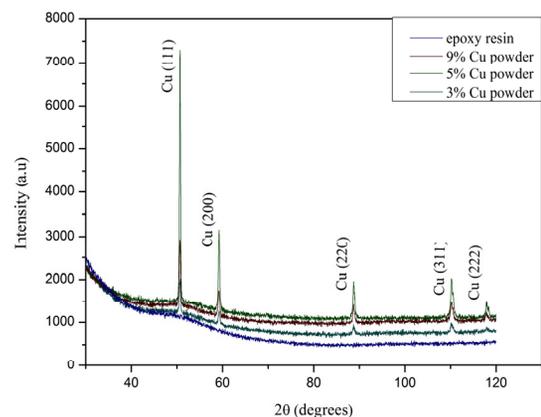


Fig. 4. X-ray diffraction of the composite polymeric materials reinforced by Cu powder

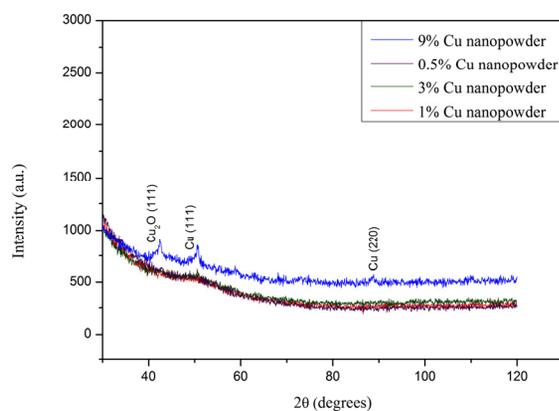


Fig. 5. X-ray diffraction of the composite polymeric materials reinforced by Cu nanopowder

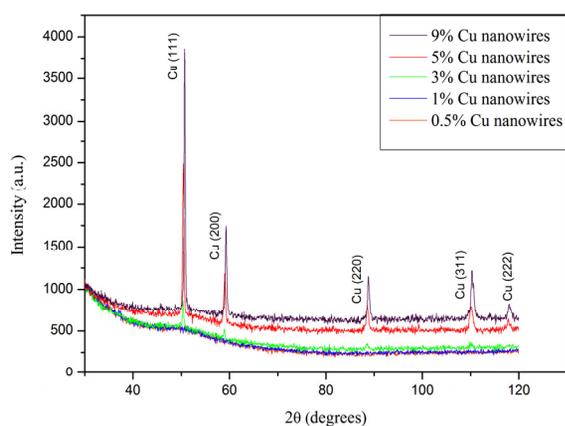


Fig. 6. X-ray diffraction of the composite polymeric materials reinforced by Cu nanowires

The composite polymeric material was subjected to infrared spectroscopic study FTIR to determine the existing bonds in the material. Figures 7 show FTIR spectroscopic epoxy resin. On the FTIR spectrum of an epoxy resin  $\text{CH}_3$  bond stretching, stretching and C-C,  $\text{CH}_2$  shuttle have been found out. The infrared spectra of composite material did not change its shape.

No changes in the occurrence of bonds by adding to the epoxy resin reinforcement in the form of powders, (micro and nanometer scales) and copper nanowires. It also shows that there has been no degradation of the polymer.

Summary analyzing spectra when added to the resin of the copper particles can be concluded that the slight differences for example in relation to the groups  $\text{CH}_2/\text{CH}_3$  may be caused by changes in chemical structure arising among others as a result of a different rate of cure of the resin resulting from the addition of copper.

Table 5.

Bonding groups and their approximate position

To determine the frequency of group	The approximate position ( $\text{cm}^{-1}$ )
$\text{CH}_3$ stretching	2960, 2850
C-C stretching	1606, 1508, 1455
$\text{CH}_2$ swing	1230

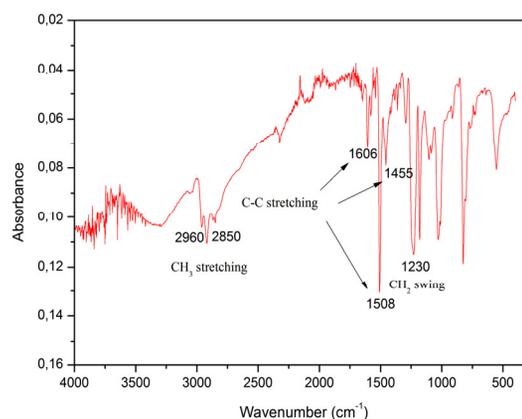


Fig. 7. FTIR spectroscopy spectrum epoxy resin

Research fracture was made using a scanning electron microscope (Figs 8-21). The structure of the turn of pure epoxy resin is characterized by smooth surface with no cracks (Fig. 8). In the case of composite polymeric materials reinforced with micrometric powder, there were no changes fracture surface is smooth and similar in appearance to the structure of the turn of the pure epoxy resin (Figs 9-11). Structures fracture of composite polymeric material reinforced with nanometer copper powder exhibit differences (Figs 12-16). Small particulates are visible that may indicate the resulting agglomerates. The most visible particles involve 9% copper nanopowder in an epoxy matrix. With smaller share of copper nanopowder particles they are not so visible, which can provide good dispersion strengthening in the matrix. In the structure of polymeric materials reinforced composite nanometer copper powder can watch a certain orientation of the particulate reinforcement in the matrix. In the case of the structure fracture reinforced polymeric composite materials of copper nanowires there were no significant differences in the microstructure (Figs 17-21). With the increase of the share gain matrix appearing particles were observed, which may indicate the formation of agglomerates. In contrast, comparing the composite material of a 9% copper nanopowder and a composite material of a 9% copper nanowires, it is clear that the nano-sized copper powder agglomeration has much more than it is the case with copper nanowires.

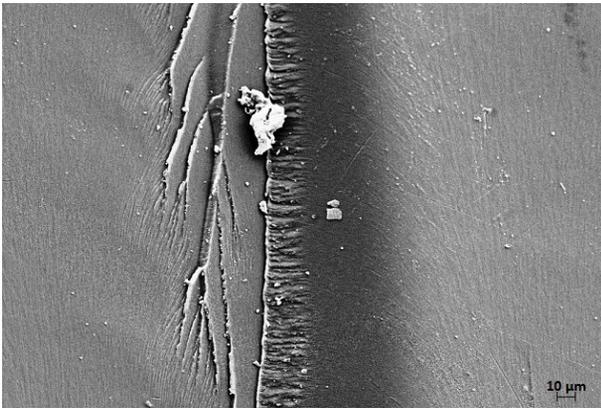


Fig. 8. The structure of the turn of the epoxy resin, scanning electron microscope

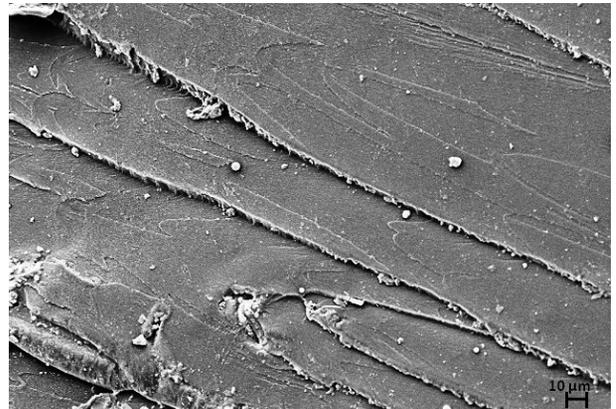


Fig. 9. The structure of the turn of the composite polymeric material having a share 3% of Cu powder, scanning electron microscope

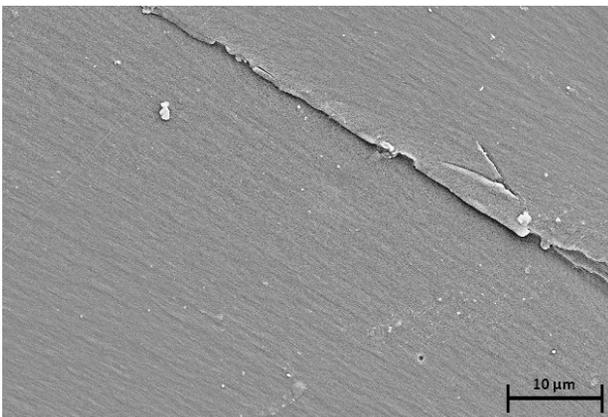


Fig. 10. The structure of the turn of the composite polymeric material having a share of 5% of Cu powder, scanning electron microscope

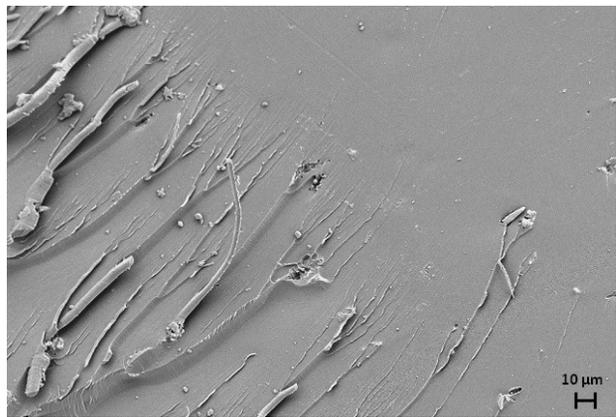


Fig. 11. The structure of the turn of the composite polymeric material having a share of 9% of Cu powder, scanning electron microscope

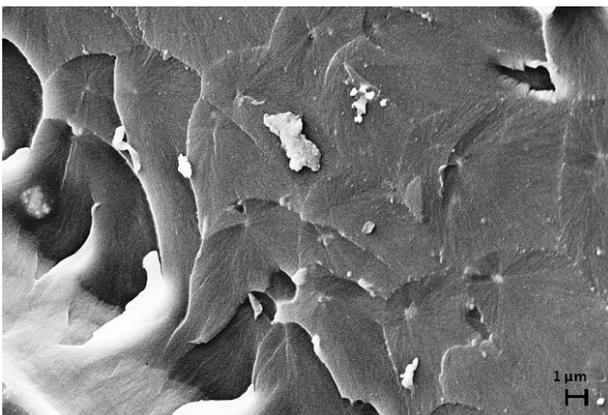


Fig. 12. The structure of the turn of the composite polymeric material having a share of 0.5% of Cu nanopowder, scanning electron microscope

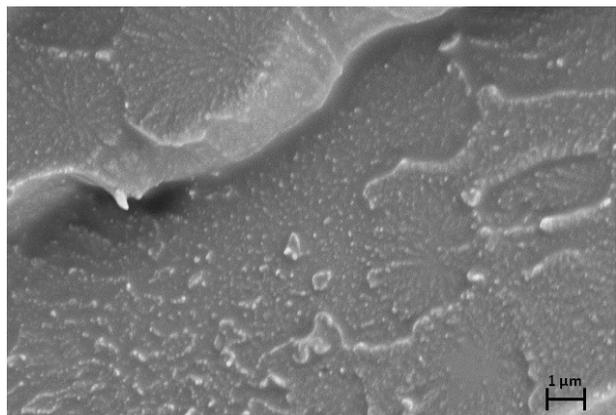


Fig. 13. The structure of the turn of the composite polymeric material having a share of 1% of Cu nanopowder, scanning electron microscope

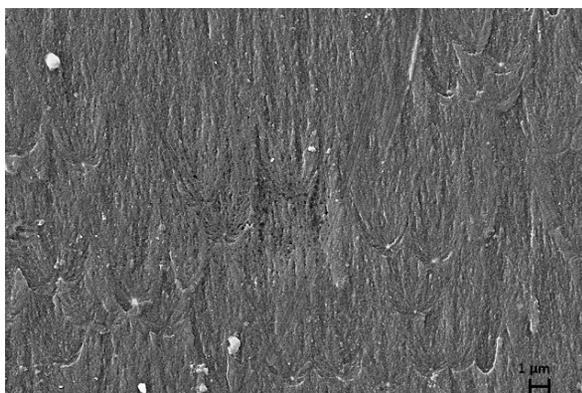


Fig. 14. The structure of the turn of the composite polymeric material having a share of 3% of Cu nanopowder, scanning electron microscope

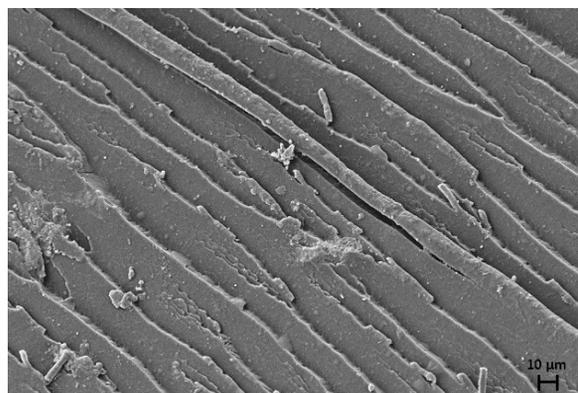


Fig. 15. The structure of the turn of the composite polymeric material having a share of 5% of Cu nanopowder, scanning electron microscope

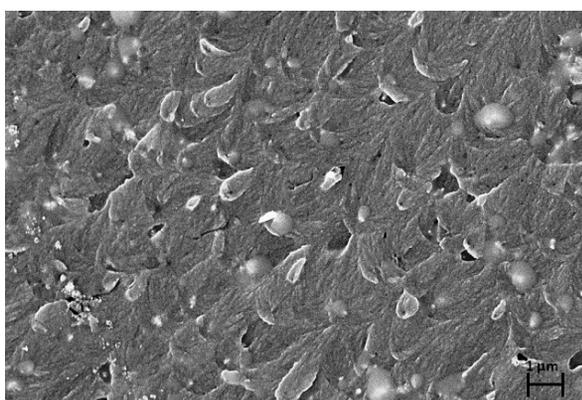


Fig. 16. The structure of the turn of the composite polymeric material having a share of 9% of Cu nanopowder, scanning electron microscope

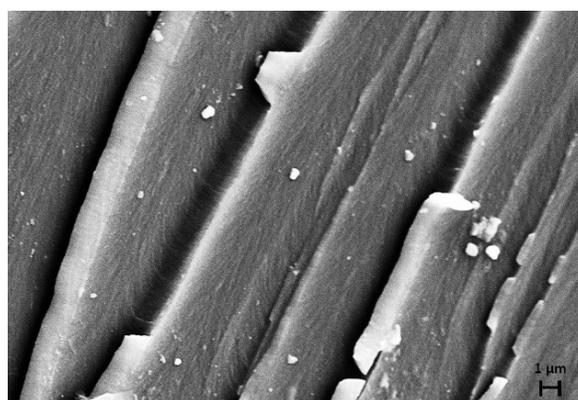


Fig. 17. The structure of the turn of the composite polymeric material having a share of 0.5% of Cu nanowires, scanning electron microscope

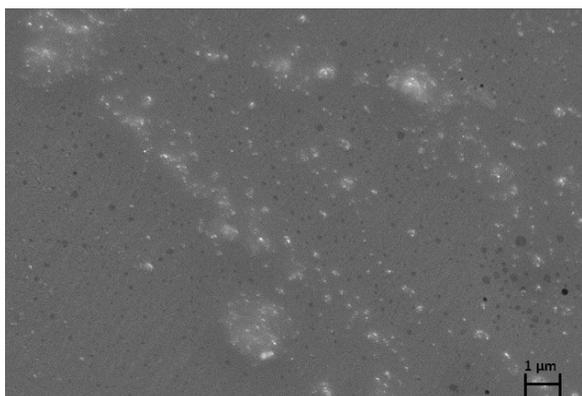


Fig. 18. The structure of the turn of the composite polymeric material having a share of 1% of Cu nanowires, scanning electron microscope



Fig. 19. The structure of the turn of the composite polymeric material having a share of 3% of Cu nanowires, scanning electron microscope

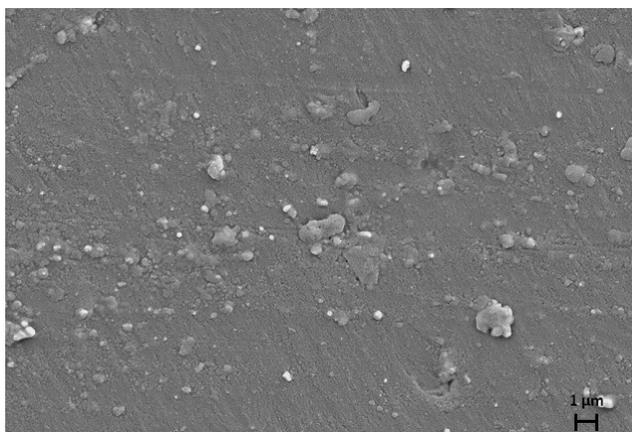


Fig. 20. The structure of the turn of the composite polymeric material having a share of 5% of Cu nanowires, scanning electron microscope

On the border reinforcement-matrix, there was no obvious defects (cracks, voids). On this basis, the placement of reinforcement in the composite material is correct. The resulting image produced microstructure of the polymeric composite materials confirmed the good connection reinforcement of polymeric matrix.

Taken spectroscopic studies of UV/Vis composite polymeric materials. In the case of the spectrum of pure epoxy resin absorbance peak is presented in the range 228-364 nm wavelength (Table 6). The spectrum for the composite polymeric material reinforced with micrometric copper powder. In this case one can determine that the peak absorbance has widened, with the result that there is a wider wavelength range 224-548 nm. Spectra absorbance UV/Vis a similar in shape regardless of the strengthening part in an epoxy matrix. The absorbance value increased slightly comparing to the pure epoxy resin. In the case of spectra for the composite polymeric material reinforced with nanometer copper powder found to shift the absorbance peak as well as the inset in relation to the composite polymer material reinforced with micrometric copper powder. The peak absorbance occurs in a wavelength range of 260-574 nm. It has also been an increase in the value of absorbance in relation to composite materials reinforced with micrometric copper powder. The absorbance spectra of polymeric materials reinforced composite nanowires copper differ in shape depending on the weight gain in the composite material. The scope of present peak absorbance is shifted to the peak absorbance for pure epoxy resin, and said extension thereof. In general, the peaks for those composite materials are included in the wavelength range 234-564 nm. For the material on the participation of 0.5% copper nanowires narrow peak absorbance was observed in the range of 234-398 nm

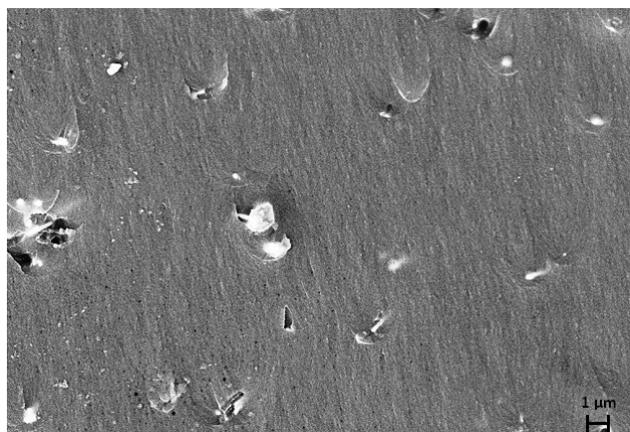


Fig. 21. The structure of the turn of the composite polymeric material having a share of 9% of Cu nanowires, scanning electron microscope

wavelength, but a relatively high absorbance value. With the increase in the share of nanowires of copper in the composite material expansion of the absorbance peak and increase its value. The most significant increase in the absorbance values and the extension of nanocomposite exhibits a peak of 9% share of the copper nanowires in the composite material. Table 6 summarizes the absorbance and wavelength for each sample

A volume resistivity test was performed in order to determine the effect of strengthening the copper composite materials of an epoxy matrix. Volume resistance indicates the ability of material to limit the flow of electrical current.

In the case of testing the minimum value of the volume resistivity of the sample they are characterized by the participation of 5% copper nanopowder ( $7.15 \cdot 10^9 \Omega$ ) and the participation of 3% copper nanowires ( $2.24 \cdot 10^9 \Omega$ ). The largest scatter of volume resistivity measurement results were found out for composite reinforced polymer materials with copper nanowires. The Table 7 shows the results of measurement of resistivity.

Tests of resistance to electrical breakdown performed on polymeric materials reinforced composite by Cu nanopowder and Cu nanowires. Table 8 presents the results of the measurement. On the basis of electric breakdown for polymeric nanocomposite materials it has been found that polymer nanocomposites reinforced Cu nanowires in a proportion of 3% to strengthen the effect of reducing the electric breakdown in comparison to the material of pure epoxy resin. For reinforcement in the form of copper nanopowder received electric breakdown test results also show a decrease of electric breakdown involving 3% gain. However, it is a smaller decrease compared to polymeric composite materials reinforced nanowires.

Table 6.  
The absorbance values and the range of the wavelength

	Type strengthening	The mass value	The absorbance value max	Wavelength range [nm]
The matrix - epoxy resin	Epoxy resin		1.33	228 - 364
	Cu powder	3%	1.38	224 - 554
		5%	1.34	230 - 554
		9%	1.27	226 - 548
		0.5%	1.78	276 - 472
	Cu nanopowder	1%	1.72	276 - 494
		3%	1.82	260 - 522
		5%	2.05	250 - 554
		9%	1.80	252 - 574
	Cu nanowires	0.5%	2.00	234 - 398
		1%	1.76	234 - 552
		3%	1.84	258 - 546
		5%	1.82	262 - 544
		9%	2.26	254 - 564

Table 7.  
The results of resistivity measurement

	Type strengthening	The mass value	Average volume resistivity [ $\Omega$ ]
The matrix - epoxy resin	Epoxy resin		$9.15 \cdot 10^{12}$
	Cu powder	3%	$3.18 \cdot 10^{11}$
		5%	$2.87 \cdot 10^{11}$
		9%	$3.40 \cdot 10^{12}$
		0.5%	$1.68 \cdot 10^{12}$
	Cu nanopowder	1%	$1.45 \cdot 10^{12}$
		3%	$4.68 \cdot 10^{10}$
		5%	$7.15 \cdot 10^9$
		9%	$2.32 \cdot 10^{10}$
	Cu nanowires	0.5%	$2.38 \cdot 10^{12}$
		1%	$1.12 \cdot 10^{11}$
		3%	$2.24 \cdot 10^9$
		5%	$1.62 \cdot 10^{12}$
		9%	$6.91 \cdot 10^{11}$

Table 8.  
Measurement results electric breakdown

	Type strengthening	The mass value	The value of an electrical fault [kV]
	The matrix - epoxy resin	Epoxy resin	
Cu nanopowder		0.5%	63.6
		1%	63.1
		3%	61.4
		5%	58.6
		9%	16.5
		0.5%	63.1
Cu nanowires		1%	63.0
		3%	57.4
		5%	13.3
		9%	10.8

#### 4. Discussion

The main aim of the research is to explain the effect of copper nanopowder and copper nanowires on the structure and properties of polymeric composite materials. Specific surface area of materials reinforcement and the percentage of reinforcement in polymeric composite material has the influence on those properties.

The specific surface area of material reinforcement is important because it affects the reactivity of the material. On the basis of made measurements a significant increase in the specific surface area together with decrease of reinforcement size (Table 4), which has an influence on the increase of the Van der Waals forces between the particles. Those results in the formation of agglomerates are difficult to break. Increasing the surface area of the strengthening also increases the interfacial area, and magnetic interactions between polymeric chains and reinforcement. The results of measurements of the specific surface area values are conventional and depend on the measurement method (Tables 3, 4). The most commonly used method is the BET considered to be the standard method. It is an analysis of nitrogen adsorption isotherms by the BET isotherm linear form. They refer to the case of physical adsorption, when it comes to form the gas layer at the interface of the test material. It is a reversible process - desorption. With the

increasing specific surface area of reinforcement, the greater the impact of the reinforcement of the matrix polymer (Figs 8-21), which is confirmed in the literature data [28-31].

X-ray diffractograms show the presence of the copper particles (Figs 4-6). In the case of polymeric nanocomposites reinforced by copper nanopowders, reflections coming from the phase of  $\text{Cu}_2\text{O}$ , which proves that oxidation of copper nanopowder, which occurred as a result of contact with the atmosphere have been found. The oxidation process takes time, but if the particle size is in the nanoscale that process occurs much faster [7,10].

Infrared spectroscopic FTIR allowed for determining the existing bonds in the polymeric composite materials (Table 5). No changes in the occurrence of bonds by adding to the epoxy resin reinforcement in the form of powders, (micro and nanometer scales) and copper nanowires have been found. It also shows that there has been no degradation of the polymer (Fig. 7).

On the basis of the outcarried studies of UV/V an increase in the absorption peak of the composite polymeric material reinforced with copper in comparison to the pure resin, and its extension in the wavelength range has been observed. The highest value of peak absorption occurs for a material with a share of 9% copper nanowires, while the largest wavelength range has been found for material with a 9% share of copper nanopowder (252-574 nm) (Table 6).

Fracture of polymeric composite materials have been observed in a scanning electron microscope (Figs 8-21). On that basis the copper nanopowder has a much greater tendency to agglomeration than it is in the case of copper nanowires. It is due to the particle size of copper nanopowder.

Defects at the interface between matrix and reinforcement have not been observed.

Experimental tests conducted on composites consisting of an insulating matrix and particles of conductive reinforcement are often analyzed using the percolation theory [23,24].

After crossing a critical concentration of reinforcement, called a percolation threshold an increase of susceptibility of the composite material on electric current. The theoretical value of a percolation threshold for randomly distributed, hard spherical particles has been measured at the level of about 16% of the volume [25,27]. Studies [23-26], which are focused on the rod-shaped reinforcements have been recently published. In that case, a considerable reduction in a percolation threshold from in relation to the increase of the ratio of length to diameter of the particle reinforcement, achieving a value of lower than 4% of volume. It has been confirmed by studies of polymeric nanocomposites reinforced copper nanowires (Figs 8-21). With the participation of 3% of copper nanowires in a matrix of epoxy resin the decrease of through resistivity and the value of electric breakdown has been found out (Tables 7, 8).

The rightness of the use of polymeric nanocomposite materials especially in copper nanowires has been shown.

Studies of copper nanowires have proved their geometrical characteristics (Fig. 2) as compared to copper nanopowder and copper powder (Figs 1, 3), which in combination with the increased surface specific area in relation to the copper powder improve the flow properties of the composite material, in particular electrical conductivity (Tables 7, 8). Nanowires have two directions of quantum-organic, but one inorganic direction of electrical conductivity [8,23,27]. It is confirmed also by the literature data [25-27], indicating that comparing to spherical particles, unique geometrical features nanowires and their electrical properties affect the increase of the conductivity of conventional materials with a polymeric matrix ( $\sim 10^{10}$  to  $10^{14}$  S/m), already at a very small participation (<1% vol.).

## 5. Conclusions

Summing up the results, it was found out that the best material for reinforcement in polymer matrix composite materials are epoxy resin copper nanowires. Thanks to

their characteristics the geometric already at small their addition improves the properties of the composite material. Undoubtedly, copper nanowires are an attractive alternative to materials such as carbon nanotubes. On the basis of obtained results polymeric nanocomposite materials reinforced copper nanowires and morphology of the copper nanowires, it appears that much easier to form in the material comprising nanowires conduction paths, so important because the electrical properties of polymeric composite materials. Contribution to 9% by weight gain in the composite material constitutes a very small value, and therefore it is appropriate for continued research in this area.

Studies surface area of reinforcement of the material showed that the copper-dimensional nanowires is an attractive material for the strengthening of polymeric composite materials. Because of their shape and dimensions, the formation of percolation paths necessary for electrical charge in the insulating matrix, are better material strengthening of copper nanopowder. The materials reinforced nanocomposite nanopowders of copper and copper nanowires show the transferability of electric charge, as confirmed by studies of volume resistivity and resistance to electrical breakdown. Thanks to its properties, those materials may gain utilitarian importance.

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## Additional information

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## References

- [1] G. Borkow, J. Gabbay, Copper, An Ancient Remedy Returning to Fight Microbial, Fungal and Viral Infections, *Current Chemical Biology* 3 (2009) 272-278.
- [2] J. Konieczny, Materials used in the construction of the Air Force, *Army* 4 (2013) 68-75 (in Polish).
- [3] L.A. Dobrzański, M. Bilewicz, J.C. Viana, Polymer nanocomposites reinforced with montmorillonite, *Archives of Materials Science and Engineering* 53/1 (2012) 5-28.
- [4] L.A. Dobrzański, Basics of design methodology material, Wyd. Pol. Śl., Gliwice 2009 (in Polish).
- [5] J.W. Gardner, P.N. Bartlett, Application of conducting polymer technology in microsystem, *Sensors and Actuators A* 51 (1995) 57-66.
- [6] L. Nicole, et al., Hybrid materials science: a promised land for the integrative design of multifunctional materials, *Nanoscale* 6 (2014) 6267-6292
- [7] H. Deng, L. Lin, M. Ji, S. Zhang, M. Yang, Q. Fu, Progress on the morphological control of conductive network in conductive polymer composites and the use as electroactive multifunctional materials, *Progress in Polymer Science* 39/4 (2014) 627-655.
- [8] D.R. Paul, L.M. Robeson, Polymer nanotechnology: Nanocomposites, *Polymer* 49 (2008) 3187-3204.
- [9] G. Zhang, Q. Yu, W. Wang, X. Li, Nanostructures for Thermoelectric Applications: Synthesis, Growth Mechanism, and Property Studies, *Advanced Materials* 22 (2010) 1959-1962.
- [10] C. Bai, M. Liu, Implantation of nanomaterials and nanostructures on surface and their applications, *Nano Today* 7 (2012) 258-281.
- [11] M. Bilewicz, K. Labisz, T. Tański, et al. Structural identification of polymer nano-composites, *Acta Physica Polonica A* 126/4 (2014) 895-901.
- [12] R.V. Kurahatti, A.O. Surendranathan, S.A. Kori, N. Singh, A.V. Ramesh Kumar, S. Srivastava, Defence applications of polymer nanocomposites, *Defence Science Journal* 60/5 (2010) 551-563.
- [13] T. Köhler, S. Mietke, J. Ilgner, M. Werner, *Nanotechnology - Markets & Trends*, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2005, 51-56.
- [14] B. Bhushan, *Springer Handbook of Nanotechnology*, Springer, Berlin Heidelberg, 2010, 119-169.
- [15] L. Peponib, D. Pugliaa, L. Torrea, L. Valentinia, J.M. Kenny, Processing of nanostructured polymers and advanced polymeric based nanocomposites, *Materials Science and Engineering: R: Reports* 85 (2014) 1-46.
- [16] P. Rana, R.P. Chauhan, Size and irradiation effects on the structural and electrical properties of copper nanowires, *Physica B* 451 (2014) 26-33.
- [17] A.D. Dobrzańska-Danikiewicz, Foresight methods for technology validation, road mapping and development in the surface engineering area, *Archives of Materials Science and Engineering* 44/2 (2010) 69-86.
- [18] A.D. Dobrzańska-Danikiewicz, Materials Surface engineering development trends, *Open Access* 6 (2011).
- [19] A. Dobrzańska-Danikiewicz, The methodology of computer-integrated forecasting the development of surface engineering of materials, *Open Access Library* 1/7 (2012) (in Polish).
- [20] PN-EN 62631-1:2011E Dielectric properties of solid insulating materials - Part 1: General (in Polish).
- [21] IEC 60243-1 Tests for thermoplastic materials used in the electrical and electronic industries.
- [22] PN-EN ISO 3252 Powder metallurgy - Vocabulary (in Polish)
- [23] J.K.W. Sandler, J.E. Kirk, I.A. Kinloch, M.S.P. Shaffer, A.H. Windle, Ultra-low electrical percolation threshold in carbon-nanotube-epoxy composites, *Polymer* 44 (2003) 5893-5899
- [24] C.A. Martin, J.K.W. Sandler, M.S.P. Shaffer, M.-K. Schwarz, W. Bauhofer, K. Schulte, A.H. Windle, Formation of percolating networks in multi-wall carbon-nanotube-epoxy composites, *Composites Science and Technology* 64 (2004) 2309-2316.
- [25] S. Mohammadzadeh, D. Pouladsaz, et al., Electronic transport properties in copper nanowire, *Microelectronic Engineering* 85 (2008) 1992-1994
- [26] G.C. Psarras, Hopping conductivity in polymer matrix-metal particles composites, *Composites: Part A* 37 (2006) 1545-1553
- [27] Y.P. Mamunya, V.V. Davydenko, P. Pissis, E.V. Lebedev, Electrical and thermal conductivity of polymers filled with metal powders, *European Polymer Journal* 38 (2002) 1887-1897
- [28] R. Pilawka, S. Paszkiewicz, Z. Rosłaniec, Epoxy composites with carbon nanotubes, *Advances in Manufacturing Science and Technology* 36/3 (2012) 67-79.
- [29] M.R. Loosa, L.A. Ferreira Coelho, S.H. Pezzin, S.C. Amico, Effect of carbon nanotubes addition on the mechanical and thermal properties of epoxy matrices, *Materials Research* 11/3 (2008) 347-352.
- [30] S.G. Prolongo, M. Campo, M.R. et al., Thermophysical characterisation of epoxy resin reinforced by amino-functionalized carbon nanofibers, *Composites Science and Technology* 69 (2009) 349-357.
- [31] W. Zhang, R.S. Blackburna, A.A. Dehghani-Sanij, Effect of silica concentration on electrical conductivity of epoxy resin-carbon black-silica nanocomposites, *Scripta Materialia* 56 (2007) 581-584.