FACULTY OF TEXTILE ENGINEERING TUL

Complex analysis of EMI shielding fabrics

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SUMMARY OF THE THESIS

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1. KAP/D126 Mathematical Statistics, 05.02.2020
2. KMI/D136 Structure and properties of textile fibers, 14.05.2020
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Research projects

1. SGS-2021-6025 Effect of geometry and concentration of fly ash and laponite on impact and dynamic mechanical properties of filled epoxy matrix, team leader, 2021
2. Hybrid Materials for Hierarchical Structures (HyHi) project (Reg. No. CZ.02.1.01/0.0/0.0/16_019/0000843), researcher, 2021-2022.
3. SGS-2022-6012 Non-woven fabrics with copper coating processed with parylene encapsulation technology, team leader, 2022.
4. SGS-2023-6375 Influence of different matrix types on selected properties of carbon fiber reinforced composites, researcher, 2023
5. GACR-project Advanced structures for thermal insulation in extreme conditions (Reg. No. 21-32510M), technician, 2023-2024
6. SGS-2024-6422 Mechanical decomposition of polyester textiles, researcher, 2024

Other projects

EMI shielding effectiveness test for company Bochemie a.s., researcher, 2020-2023

Abstract

Numerous papers have proved that using textile-based material with a functional coating is an effective method for electromagnetic interference (EMI) shielding in real conditions. Comparing with metallized materials incorporated into woven fabric substrates, nonwoven surface coated fabrics are progressively gaining extensive application in electromagnetic shielding materials owing to their expeditious production, cost-effectiveness, flexible thin structure, and facile processing.

However, for surface coated nonwoven fabrics by metal particles, the shielding effectiveness is often limited due to structural arrangement of fibrous phase. The structural modeling and simulation of electromagnetic shielding performance remain generally under-researched areas. There is also a lack of studies for electromagnetic shielding effectiveness prediction by mathematical models. In practical applications, the contradiction between the wash resistance and breathability of metal particles surface coated textiles has been a persistent challenge. Many studies that focus on enhancing the wash resistance of these materials often neglect or unavoidably compromise their breathability. Additionally, the relatively weak mechanical properties of textiles further limit the application of metal particles surface coated textiles in electromagnetic shielding under harsh environmental conditions.

This dissertation is in form of a comprehensive commented scientific articles published by me in impacted journals regarding to solve above problems. Via multilayer structure without altering the type of metal particles in the coating, the electromagnetic shielding effectiveness of metal particles surface coated textiles is effectively enhanced more than 88% with 5 layers structure. Through the successful development of simulation methods and mathematical prediction models, this work provides effective tools for designing and studying the electromagnetic shielding properties of metal particles surface coated textiles. Additionally, by encapsulating Parylene-C via chemical vapor deposition techniques, the encapsulated samples achieve a balance between wash resistance and breathability in metal particles surface coated textiles.

This PhD work made deeper and systematic research on EMI shielding of metal particles surface coated textiles. The results not only fill the gap in electromagnetic shielding simulation and shielding effectiveness prediction models for metal particles surface coated nonwovens but also successfully resolve the conflict between wash resistance and breathability. Additionally, this work proposes an effective method for enhancing the electromagnetic shielding performance of metal particles surface coated textiles through multilayer structures. The results of this doctoral thesis provide more theoretical research basis for the design and production of high-efficiency electromagnetic shielding textiles, expand the scope of application environment, and will be of great help in the future, especially for the application of metal particle plated nonwovens in the field of electromagnetic shielding.

Key words: EMI shielding, metal particles surface coating, geometrical modeling, EMI shielding simulation, mathematical prediction model, washing durability, breathability

Abstrakt

V mnoha studiích bylo prokázáno, že použití textilních materiálů s funkční povrchovou úpravou je účinným postupem pro stínění elektromagnetického rušení (EMI) v reálných podmínkách. Ve srovnání s metalizovanými materiály začleněnými do tkaných textilních substrátů získávají netkané textilie s povrchovým nánosem kovů stále širší uplatnění v elektromagnetických stínicích materiálech díky jejich rychlé výrobě, nákladové efektivitě, flexibilní tenké struktuře a snadnému zpracování.

U netkaných textilií s povrchovou úpravou kovovými částicemi je účinnost elektromagnetického stínění často omezena díky strukturnímu uspořádání vlákenné fáze. Strukturální modelování a simulace elektromagnetických stínicích vlastností zůstávají obecně málo prozkoumanými oblastmi. Rovněž chybějí studie pro předpověď účinnosti elektromagnetického stínění pomocí matematických modelů. V praktických aplikacích představuje rozpor mezi odolností proti praní a prodyšností textilií s povrchovou úpravou kovovými částicemi trvalou výzvu. Mnoho studií zaměřených na zvýšení odolnosti těchto materiálů proti praní často zanedbává nebo nevyhnutelně snižuje jejich prodyšnost. Navíc relativně nízká úroveň mechanických vlastnosti textilií s povrchovou úpravou kovovými částicemi dále omezují jejich použití pro elektromagnetickém stínění za náročných environmentálních podmínek.

Tato disertační práce má formu souhrnných komentovaných vědeckých článků, které jsem publikoval v impaktovaných časopisech za účelem řešení výše uvedených problémů. Použitím vícevrstvé struktury je účinnost elektromagnetického stínění textilií s povrchovou úpravou kovovými částicemi účinně zvýšena o více než 88 % při pěti vrstvách, aniž by se měnil typ kovových částic v povrchovém nánosu. Na základě výrazného vývoje simulačních metod a matematických predikčních modelů byly v této práci vytvořeny efektivní nástroje pro navrhování a studium elektromagnetických stínicích vlastností textilií s povrchovou úpravou kovovými částicemi. Navíc povlakem pomocí technik chemické depozice Parylenu-C z plynné fáze bylo dosaženo jak zvýšené odolností proti praní, tak i prodyšnosti u textilií s povrchovou úpravou kovovými částicemi.

V této disertační práci je proveden hlubší a systematický výzkum EMI stínění textilií s povrchovou úpravou kovovými částicemi. Získané výsledky nejen odstraňují nedostatky v simulacích a modelování elektromagnetického stínění pro předpovědi účinnosti stínění pro netkané textilie s povrchovou úpravou kovovými částicemi, ale také úspěšně řeší problémy s odolností proti praní a prodyšností. Tato práce rovněž navrhuje efektivní metodu pro zvýšení elektromagnetických stínicích vlastností textilií s povrchovou úpravou kovovými částicemi pomocí vícevrstvých struktur. Výsledky této disertační práce poskytují hlubší teoretický základ pro návrh a výrobu vysoce účinných textilií pro elektromagnetické stínění, rozšiřují rozsah použitelnosti a budou využitelné, zejména pro aplikaci netkaných textilií pokovených kovovými částicemi v různých oblastech elektromagnetického stínění.

Klíčová slova: EMI stínění, povrchový nános kovových částic, geometrické modelování, simulace EMI stínění, matematický predikční model, odolnost v praní, prodyšnost

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List of abbreviation

CF: Carbon Fiber

CNT: Carbon Nanotube

CuPET: Purchased commercial Cu coated PET nonwovens

CVD: Chemical Vapor Deposition

EDS: Energy Dispersive Spectroscopy

EMI: Electromagnetic Interference

GSM: Global System for Mobile Communications

HFSS: High Frequency Structure Simulator

MXene: Two-dimensional inorganic compounds, that consist of atomically thin layers of transition metal carbides, nitrides, or carbonitrides

PANI: Polyaniline

PET: Polyethylene Terephthalate

PETCu: Copper particles coated polyester nonwoven fabric

PPy: Polypyrrole

SE: Shielding Effectiveness

SEM: Scanning Electron Microscopy

List of symbols

C: Constant value for calculating the total shielding effectiveness

f : Frequency (Hz)

H_0: Null hypothesis

H_1: Alternative hypothesis

l : The maximum pore dimension of the fabric (m)

K: Electrical conductivity (S/m)

K_r: Relative conductivity of metalized textile to copper

K_{Cu}: Electrical conductivity of copper (S/m)

n : number of pores

n_{cal} : numbers of pores in the calculation area for EMI shielding test of the sample

t： thickness of the sample (m)

SE: EMI shielding effectiveness (dB)

SE_A: EMI shielding effectiveness from material absorption attenuation (dB)

SE_B : EMI shielding effectiveness from material internal multireflection attenuation (dB)

SE_R : EMI shielding effectiveness from material reflection attenuation (dB)

SE_{foil}: EMI shielding effectiveness from the foil effect (dB)

SE_{pore}: EMI shielding effectiveness from the pore effect (dB)

SE_{total} : EMI shielding effectiveness of the total effective from foil and pore (dB)

SEG : Specific electromagnetic shielding effectiveness based on planar density (dB·m²/g)

V_{pore} : Volume of pores (m^3)

w : planar density (m²/g)

μ : magnetic permeability (H/m)

μ_r: relative magnetic permeability

μ_s : EMI shielding effectiveness value from simulated result (dB)

μ_m : EMI shielding effectiveness value from experiment measured result (dB)

δ: Skin depth (m)

Content

1. Introduction

With the increasing demands for electronic devices and the rapid development of telecom technology, the excessive electromagnetic wave could increase the health risks for worker or pregnant women who prolonged exposed in the massive electromagnetic radiation environment[1–3], and the extra electromagnetic interference (EMI) could damage the equipment which is sensitive to strong electromagnetic filed[4–7]. Numerous research and production have proved that using textile-based material with a functional coating is an effective method for EMI shielding in daily life[8]. The main advantage of textile-based EMI shielding material similar to polymer matrix EMI composites is its lightweight and multifunction compatibility for EMI shielding application[9]. The utilization of EMI shielding technical clothing as a means to impede extraneous electromagnetic radiation has been endorsed as an effective method for EMI shielding. This approach demonstrates proficiency in attenuating the propagation of electromagnetic radiation through efficient mechanisms such as reflection, absorption, and multi-reflection within the material(Figure 1) [10–12]. Among these, the conductive textiles constructed by incorporating metal particle coatings onto fabrics through mass-producible methods such as electroless or electroplating, emerge as prototypical representations. The prevalence of these metalized textiles is notable, particularly in their application as materials for EMI shielding clothing.[13–16].

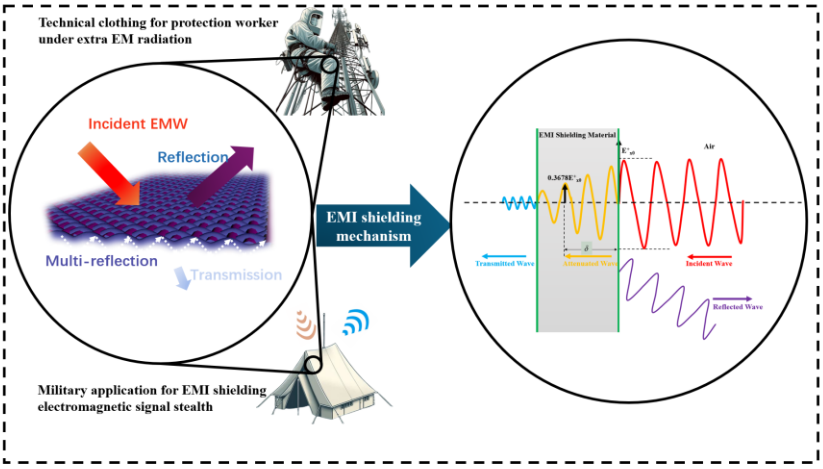


Figure 1 (a) Main application of EMI shielding textiles and the mechanism of EMI shielding from metalized fabrics

This metalized textile has excellent wearing properties which is contributed from the textile fiber such as soft texture, good water vapor and air permeability, washing durability. Regarding the metalized textiles for EMI shielding application, the main research aspects are focused on the following points:

1) New conductive material, especially MXene-based composite fabric for EMI shielding application
2) Novel structure design for enhancing the EMI shielding property
3) Material finishing and surface treatment for improve the mechanical property or other wearing comfort properties aiming of technical clothing application.
4）Modeling and mechanism study of metalized textile for EMI shielding application.

From the scope of the main research aspects regarding to metalized textiles for EMI shielding, it’s clearly to see that the development trend of textile-based EMI shielding material is developing lightweight design, suitable for more complex external environments and improves wearing comfort when used in technical clothing EMI shielding textiles. Considering in the military application, the use of chemical fiber metal bending processing technology and textile processing technology to manufacture left-handed materials is an important topic worthy of research. When an object is enclosed by a negative refractive index material, the electromagnetic wave (or light wave) bends and detours on the surface of the enclosure and does not carry the information of the enclosure and the internal object, so the detector (or observer) cannot detect the target, thus achieving the purpose of stealth.

After reviewing all the research aspects to metalized textiles for EMI shielding, the limitations of metallization were clearly presented.

The main realization method of metallized textiles including metallic fiber blending, electroplating and electroless plating, vacuum magnetron sputtering. Metal fiber blended textiles are not the first choice for electromagnetic shielding protective clothing due to their hardness and processing difficulty. For other methods of metallizing textiles, the combination of metal atoms and textile macromolecules has always been a problem that needs to be considered. The strength of the bonding ability directly affects the service life of metallized textiles.

Improving the conductivity of materials can effectively enhance the electromagnetic shielding effectiveness of materials, but the practice of simply using high-conductivity precious metals to improve electromagnetic shielding effectiveness is very limited. For example, through literature review, using silver particles to metallize textiles for electromagnetic shielding is a common method. However, the synthesis cost of nanosilver particles is very high, and the electromagnetic shielding effectiveness of the product is not significantly improved compared to electromagnetic shielding textiles metallized with copper particles.

Considering the application scenarios of electromagnetic shielding fabrics in clothing, washability is very important. However, for most metallized textiles, their washability is poor, because the binding force between metal atoms and textile fiber macromolecules is weak. Therefore, the washability of metallized textiles is an issue that needs to be solved.

As an important type of textile, nonwoven fabrics are increasingly used in electromagnetic shielding textiles due to their advantages such as high production rate and low cost. Major obstacle is dimensional instability which can be solved by using special type of nonwovens having dense network of binding points. Nonwoven fabrics can be used to create textiles with larger porosity compared to woven fabrics and knitted fabrics. Larger porosity means high air permeability which has positive influence on the wearing comfort. However, the corresponding research on the electromagnetic shielding effect of metallized nonwoven fabrics, modeling research and mathematical model research are not very in-depth.

In response to the limitations of metallized textiles discussed above and the research gaps in metal particles surface coated nonwovens in electromagnetic shielding simulation and modeling, this dissertation, through systematic research, achieved the metal particles surface coated nonwovens through the chemical plating method with excellent EMI shielding property. In A1, I published the paper with the novelty of enhancing the EMI shielding effectiveness via multilayer structure. By using the optimized nonwoven model in the constructed wave guide environment, the EMI shielding simulation for metal particles surface coated nonwoven fabrics were successfully developed, which described in my published paper A3. After conducting a systematic exploration of the model research of metal particles surface coated nonwovens, the geometrical model and mathematical EMSE prediction model were successfully developed regarding to my published paper A2 and A4, which filled the blank of modeling research for EMI shielding application. To solve the poor washing durability of metalized textiles for EMI shielding, the Parylene encapsulation method was applied which solved the conflict of washing resistance coating and air permeability of metalized EMI shielding textiles, a detailed discussion in given about this topic in the appendix A5. The motivation and novelty of the whole thesis was presented in the Figure 2.

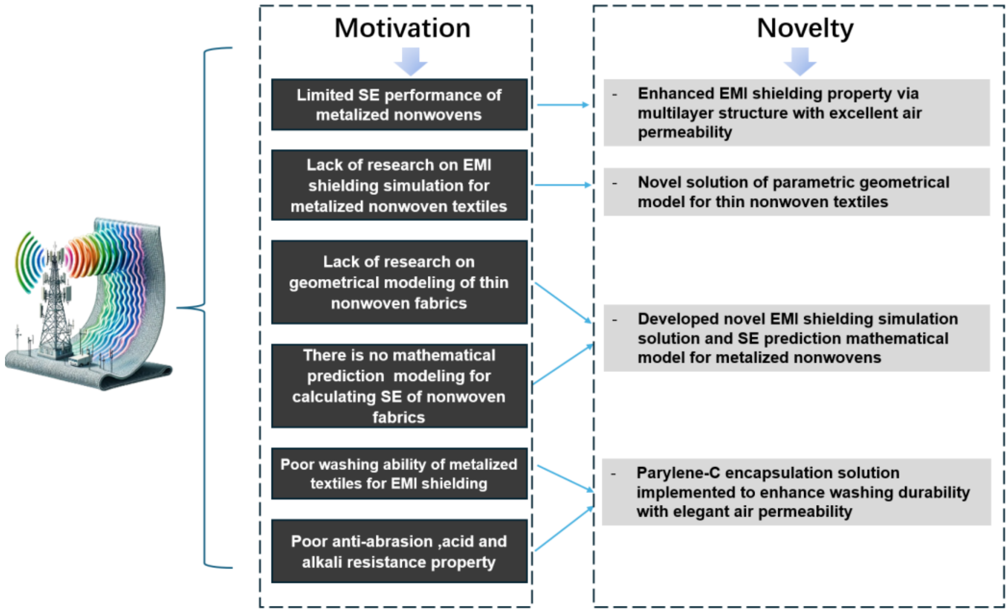


Figure 2 Summary of problems solved in this paper and new results in this thesis

2. State of art

2.1 Development on metallization of textiles and its application

The modern realization of metallized textiles commenced in the 1930s with fabrics coated in gold and silver[17]. Since that time, advancements in materials engineering have significantly transformed the appearance and functionality of these textiles. Today, metallized textiles are extensively utilized in both apparel and technical textiles due to their distinctive aesthetics and functional properties[18]. The contemporary integration of metallized materials into textiles can be categorized into two primary technologies: metal material integration and textile metallization [19]. Metal material integration entails the direct application of metallic elements, including metal filaments, metallic foils, or sheet metals, onto fabrics to achieve specific design outcomes. Textile metallization, on the other hand, is achieved by coating textile surfaces with metallic particles to create a fine metal layer.

In the context of metal material integration, metal fibers are predominantly employed. Over the past two decades, metal fiber and its products have emerged as new industrial materials, characterized by high technological sophistication and added value [20].These fibers not only possess the softness of chemical and synthetic fibers but also exhibit the excellent thermal conductivity, electrical conductivity, corrosion resistance, and high-temperature resistance inherent to metals. Blending metal staple fibers with other textile staple fibers is an effective method for creating metallized textiles[21]. Metal fibers, such as silver and stainless steel with fineness in the tens of microns, can be produced through various metal wire production processes or obtained via metal plating methods. Common textile processing techniques for producing metallized textiles include blending, interweaving, and paralleling these fibers. Mature and cost-effective methods for preparing metal-integrated fabrics include core-spun techniques, embroidery, and non-woven processes [22]. Among these, stainless steel fiber is the most widely used and studied. The preparation methods for surface-metallized functional textiles vary according to their intended use. Currently, the commonly employed methods for the mass production of surface-metallized functional textiles include electroless plating, coating, vacuum plating, and electroplating[23].

Metallic textiles possess a wide range of applications in industries requiring properties such as reflectivity, electrical conductivity, and thermal resistance. Historically, in the past century, metallized textiles were primarily utilized for decorative purposes or as protective armor. However, the rapid advancements in the electrical and telecommunication industries have transformed metallized textiles into advanced materials for diverse applications. By integrating the comfort characteristics of greige textile materials with the superior electrical properties of metals, metallized textiles have emerged as wearable conductive materials. Conductive clothing made from these textiles is capable of providing electromagnetic interference (EMI) shielding, offering protection to individuals sensitive to electromagnetic radiation. Additionally, conductive textiles find applications in the aviation and automotive industries[24]. The inherent antimicrobial properties of metals such as silver or copper enable metal-integrated textiles to excel as antimicrobial materials, which is particularly beneficial for medical textiles. In the rapidly evolving field of smart textiles, metallized textiles facilitate the transmission of bioelectric signals via conductive yarn to monitors, enabling the collection of movement or other physical activity data [25].

Despite recent advancements in metallized textiles, several challenges persist. For instance, washing durability remains a critical issue for most metallized textiles designed for technical clothing applications [23]. Additionally, the poor mechanical properties of metallized textiles can limit their longevity. Moreover, recycling metallized textiles presents a significant challenge for waste processing [26].

2.2 EMI shielding performance of metalized textiles

Applying conductive material into textile structure is one of the effective methods to realize the function of EMI shielding. Research on metal-coated textiles has demonstrated their effectiveness in EMI shielding across various applications. Compared to other EMI shielding materials such as metals, carbon-polymer composites, and nanofibrils, conductive textiles exhibit not only excellent EMI shielding performance due to their textile-based structure but also superior wearable properties, including air permeability and thermal characteristics. In this condition, the conductive fibers or particles should have even and continuous distribution.

A common method for preparing electromagnetic shielding textiles involves blending, interweaving, and arranging metal fibers or metallized fibers parallel with ordinary fibers. These textiles possess excellent wearable properties, such as a soft texture, good moisture absorption, air permeability, and resistance to washing. For instance, Xinjin Liu et al. tested fabrics made from various proportions of blended stainless-steel fiber and polyester fiber yarns for EMI shielding properties. They found that within the frequency range of 300 kHz to 3 GHz, the shielding effectiveness ranged from 20 dB to 40 dB, indicating a good electromagnetic shielding effect[27]. Additionally, Das et al. discovered that fabrics made entirely of stainless-steel fiber exhibited superior shielding performance compared to those made from a blend of stainless steel fiber and polyester yarn[28]. Conductive polymer fibers are also widely utilized in protective textiles. For example, Munan Qiu et al. prepared polyaniline (PANI) nanofiber, which achieved an electromagnetic shielding effect of 20.7 dB with a sample thickness of only 0.35 mm[29]. Furthermore, the polythiophene/polyethylene terephthalate (PTh/PET) fiber prepared by Erdoğan et al. demonstrated a shielding effect of 21 dB in the frequency range of 0-100 MHz [30].

2.3 EMI shielding modeling and simulation solution development

The methodologies of textile geometrical modeling and simulation enable efficient and accurate analysis of textile structures and prediction of their performance, thereby providing effective tools for the design and development of new products. The geometrical modeling offers an analytical perspective on the mechanics of fabrics, contributing to a deeper understanding of how these fabrics behave under various forces conditions. An outline of the various ways to deal with building the geometry of textiles at the yarn level via topology knowledge, where the 3D model of the textiles is calculated dependent on data from intersection points between the yarns is showed by Kyosev[31]. A few textile structures such like woven, knitting structures and braiding structures are discussed. Regarding the woven fabrics modeling research, M. Boljen and S. Hiermaier [32] likely discusses a framework for the continuum constitutive modeling of woven fabrics, providing insights into the mechanical behavior of these materials under various conditions. This approach would enhance the understanding of fabric properties at a macro-scale, relevant for applications in composite materials and engineering. By K. Bukenya et al. [33] likely explores the simulation of weaving processes, offering insights into optimizing manufacturing techniques for efficiency and material characteristics. This research could contribute to improvements in textile production workflows and material quality. Z. Deng and Lijing Wang [34] presents advancements in the visualization techniques of simulated woven fabrics, which is critical for designers and engineers to accurately predict the aesthetics and functionality of fabric-based products before prototyping. S. Herath [35]explores the use of Gaussian processes in the multiscale modeling of woven textiles, presenting a novel method for predicting the behavior and properties of fabrics across different scales. Similar with the woven structed textile geometrical modeling, for knitted fabrics, efforts to achieve yarn-level detail in fabric modeling, enhancing the realism of simulations are still deeply studied by many researchers. S. Ionesi et al.[36] explores methods commonly used in the geometrical modeling of knitted fabrics, likely focusing on the shape and structural aspects crucial for 3D modeling and simulation. M. Dimitriyev and Elisabetta A. Matsumoto suggests that geometrical modeling of knitted fabrics should account for both the geometry and mechanics of the fabric to comprehensively understand its structure and behavior[37,38]. T. Wada et al. [39] introduces a new physical model for controlling the deformation of plain knitted fabrics, aiming at automation in the garment industry and improved machine handling of fabrics

Material geometrical modeling is the first step in simulating the textile performance, including EMI shielding effectiveness (SE). The material structure significantly impacts the final EMI shielding performance Many studies find the EMI shielding simulation solution suitable for predicting and improving textile-based EMI shielding performance.

Utilizing the advanced capabilities of Ansys HFSS software, Rybicki [40] executed a pioneering simulation to evaluate the electromagnetic interference (EMI) shielding efficacy of woven textile samples that had been treated with a polymer coating. This innovative research, documented in reference, marks a significant stride in the understanding of EMI shielding behaviors in treated textiles. Similarly, Luis Martins[41] undertook a detailed simulation study on the EMI shielding characteristics of thermoplastics embedded with short conductive fibers, revealing that these composites exhibit superior EMI shielding effectiveness compared to traditional steel sheet venting grids, as outlined in reference. Adding to this body of knowledge, Sima Kashi's[42] simulation work, as reported in reference, accurately forecasted the effective EMI shielding capabilities of polylactide (PLA) nanocomposites infused with 15 wt.% graphene nanoplatelets (GNPs) across the entirety of the X-band frequency spectrum. These studies collectively contribute to the expanding repository of knowledge on EMI shielding materials and their simulation. A.P. Periyasamy et, al [43] utilizes a neural network model to study the EMI shielding effectiveness of Ni/Cu-coated polyester fabrics. It was found that a 25% concentration of Ni/Cu on polyester materials delivers an EMI SE of approximately 26.86 dB at 1.5 GHz, indicating very good EMI shielding capabilities suitable for both general and professional applications

Despite these advances, a prevailing challenge in the simulation of EMI shielding performance remains the limited applicability of most existing simulation software, which predominantly accommodates textiles with simple structures such as plain board and small sample sizes. This limitation is primarily due to the constraints inherent in the simulation software and the computational capacity available. The current landscape of simulation technology lacks specialized software capable of accurately modeling the intricate structures of nonwoven textiles for EMI shielding performance simulations. Nonwoven textiles, with their complex and detailed structures, present a significant challenge for simulation approaches traditionally designed for simpler industry objects. The attempt to integrate a complete mesoscale nonwoven textile geometric model into existing simulation frameworks frequently results in software malfunctions or prohibitively long simulation times, often exceeding four hours for a single sample, rendering the process impractical. Consequently, the simulation of EMI shielding properties in nonwoven textiles with intricate designs, by adjusting critical textile parameters, remains a daunting task.

2.4 EMI shielding mathematical shielding effectiveness prediction model

To investigate and develop materials with a high electromagnetic shielding effectiveness (EMSE), the utilization of a proper mathematical model becomes indispensable for the analysis and prediction of EMI shielding performance. As one of the basic principles for EMI shielding mechanism, the transmission line theory which developed by Donald R.J White in 1971 has been used as start point for developing the empirical mathematical model of electromagnetic shielding effectiveness[44]. In the transmission line theory, the incident electromagnetic wave can be attenuated by reflection loss, absorption loss and multireflection loss inside the material. Regarding the textile based shielding material, detailed EMSE mathematical model for metalized textile shields was proposed afterwards by Arthur R. Henn and Richard M. Cribb in 1992[45]. In their study, the semi-empirical model describing the SE of metalized both woven and non-woven fabrics was developed. Later in 1995, several correction values were added to the basic transmission line models after considering the leakage through openings in metalized textiles, which including the correction coefficient to considering the number of like discontinuities, the low-frequency correction coefficient considering the skin depth, the correction coefficient considering the coupling between adjacent pores[46]. Further complete derivation and verification of this model and apply the model for metalized woven fabrics was done by Marek Neruda and Lukas Vojtech [47].

According to the classic transmission line theory of electromagnetic shielding, the shielded electromagnetic wave is divided into three parts: one is the surface reflection of the shield (SE_R), the other is the absorption of the shield (SE_A), and the third is the multiple reflection inside the shield (SE_B) (Fig.2). The total shielding effectiveness for the foil (SE_{foil}) could be expressed in Eq. (1)

$$SE_{foil} = SE_R + SE_A + SE_B \quad (1)$$

$$SE_R = 168.14 + 20 \cdot \log\left(\sqrt{\frac{K_r}{f\mu_r}}\right) \quad (2)$$

$$SE_A = 8.6859 * \frac{t}{K} \quad (3)$$

$$SE_B = 20 \cdot \log\left(1 - e^{\left(\frac{-2t}{\delta}\right)}\right) \quad (4)$$

$$\delta = \frac{1}{\sqrt{\pi f \mu K}} \quad (5)$$

K is the conductivity, t is the thickness of the sample, f is the frequency, μ_r is the relative permeability, Kr is the relative conductivity of metalized textile, δ is the skin depth. Except for the blocking mechanism of EM wave from conductive foil shielding effectiveness (SE_{foil}), the pores of the shielding material also contribute to the shielding performance[48,49]. In this case, the total SE (SE_{total}) mathematical model has been developed depending on a linear combination of the SE of the foil material SE_{foil} and the blocking effect contributed by the pores SE_{pore} in the following form.

$$SE_{pore} = 100 - 20 \cdot \log(l \cdot f) + 30\frac{t}{l} \quad (6)$$

$$SE_{total} = e^{-C \cdot l\sqrt{f}} SE_{foil} + (1 - e^{-C \cdot l\sqrt{f}}) SE_{pore} \quad (7)$$

where l is the maximum aperture dimension of the fabric, C is the constant value, the calculation process please refer to the Appendix 4 (A4).

From the literature review, there is rarely no detailed study to solve the mathematical modeling problem for nonwoven metalized fabrics, only in the research of Arthur R. Henn and Richard M. Cribb described the mathematical model for metalized nonwoven fabrics (this model also designed for metalized woven fabrics) but not suitable anymore for the high porosity thin nonwoven fabrics, the compatibility and results accuracy from this model is relatively low [45]. One of the primary factors contributing to this knowledge gap is the intricate nature of nonwoven structures. Unlike woven fabrics, nonwovens exhibit random fiber distribution, owing to the diverse fabrication methods employed. Consequently, accurately describing the pore parameters of nonwovens within the electromagnetic shielding model becomes exceedingly challenging, which cannot easily use these structure parameters for metalized nonwoven fabrics.

2.5 Washing durable treatment of metalized textiles

Qi-Wei Wang et al. [50] reported that silicon-coated MXene-decorated polyester textiles exhibit exceptional electromagnetic interference (EMI) shielding properties, achieving approximately 66 dB. Furthermore, these textiles maintain stable EMI shielding performance (>30 dB) after multiple wash cycles using commercial detergent solutions. Di Xing et al. [11] developed polyurethane film-covered carbon fabric embedded with silver particles, demonstrating high conductivity and extremely high shielding effectiveness (SE) of 102.98 dB. However, the air permeability and washability of this material were not evaluated. Lihua Zou et al. [51] reported that polyaniline (PAni)-coated fabric, enhanced with carbon nanotube (CNT) coating, achieves good SE around 23 dB with a high absorption ratio. After washing with standard laundry detergent (OMO brand), the average SE of the coated fabric was reduced to 21.1 dB. Unfortunately, the air permeability of this fabric was also not assessed.

From the reviewed research, it is evident that while a certain degree of wash resistance is assured, the air permeability of treated fabrics is often significantly compromised, potentially rendering them nearly airtight. For instance, as referenced by Wang et al. [50], the air permeability of a silicon-coated sample was approximately 130 mm/s. The choice of coating technology and the material used for the protective layer significantly impacts the fabric's breathability.

3. Motivation of thesis

The innovations of this doctoral dissertation are mainly concentrated in the following points:

1) The metal particles surface coating of nonwovens realized from chemical plating. The excellent electromagnetic shielding performance was achieved under relatively high porosity conditions. Improving electromagnetic shielding performance by simply increasing the conductivity of conductive particles is very limited. Through the study of the electromagnetic shielding mechanism, the electromagnetic shielding performance was significantly improved by changing the structure of the material through a multi-layer structure on the same metalized textile material (A1). This provides more options and theoretical support for improving the electromagnetic shielding performance of metallized textiles development in the future.
2) Modeling and simulation of the electromagnetic shielding performance of metal particles surface coated nonwovens. Due to the random arrangement of fibers, the accurate modeling of nonwovens has always been a hot issue in textile modeling research. The paper calculated the fiber inclination and angle through image analysis, conducted a systematic mathematical analysis of these data, and generated an accurate structural model through program scripts. Based on this model, structural parameters such as the porosity of the material can be analyzed more accurately (A2).
3) The electromagnetic shielding effectiveness simulation of metal particles surface coated nonwovens. The paper effectively converts the nonwoven model into an equivalent simulation model to adapt to the simulation environment of the waveguide. Compared with the results of actual tests, it is verified that the newly created simulation method is suitable for metal particles surface coated nonwovens (A3). Based on this simulation method, a mathematical model for predicting the electromagnetic shielding effectiveness of metallized nonwovens is also proposed in this paper, filling the gap in the electromagnetic shielding prediction model for metallized textiles (A4).
4) Improving the poor washability after metallization, and the poor mechanical properties-which limits their application scenarios for electromagnetic shielding. This paper effectively solves the washability and breathability of metallized textiles through the application of Parylene-C chemical deposition method. After being compounded with carbon fiber, the composite material has not only been significantly enhanced in electromagnetic shielding, but also has greatly improved mechanical properties (A5).
5) Parylene packaging technology solves the human body's allergic reaction to direct contact with metal particles, and also limits the pollution caused by the shedding of copper particles from textiles in a humid and frictional environment. On this basis, the application of copper-plated textiles in the field of hyperthermia has been expanded.

4. Metal particles coated nonwovens with enhanced EMI shielding performance

In this paper, there are two groups of metalized nonwovens used in this research.

One group is made from lab by electroless plating method realizing different coating amount of copper particles. The lab-made copper coated special nonwovens MILIFE (JX Nippon ANCI Corporation.) were renamed as PETCu series for briefly. Milife materials are supplied in a planar weight of 5−60 g/m^{2,} a thickness of 0.05−0.17 mm, and a strength of 20−300 N per 5 cm of width. Composite nonwoven fabrics (combination of machine direction and cross-direction-oriented nonwoven layers) from polyethylene terephthalate and polyethylene isophthalate copolymer with 10 g/m^2 were used. The PETCu series samples were used for EMI shielding mechanism research and EMI shielding simulation solution development (Table 1).

Considering the requested size of sample and ensure the better homogeneity of the material, in this study, another group of copper-coated nonwoven fabric, commercial named “MEFTEX,” was purchased from Bochemie a.s, Czech Republic. Meftex was produced via a patent pended technological process based on subsequent chemical and continuous electroplating processes. The Meftex series samples were renamed CuPET series for brevity in this paper and used for mathematical modeling, washing durability and composites material development study.

4.1 Fabrication of metalized thin nonwovens

MILIFE is nonwoven fabric constructed from aligned warp PET/PEI monofilaments and weft PET/PEI monofilaments via a thermal bonding method. The irregular orientation of the fibers, which deviates from a regular net structure, is primarily due to inaccuracies in industrial fabrication. This fiber orientation and structure cannot be altered due to the solid bonding spots; thus, the actual structure reflects a deviation from the ideal net configuration. The basic information of the greige nonwoven fabric, as provided in the technical sheet of MILIFE, is listed in Table 2.

The electroless deposition method was utilized to deposit copper particles onto polyester nonwoven fabrics (PETCu) (Figure 3). This experimental process comprised three steps. The first step involved surface treatment, where the nonwoven polyester fabric was treated with 2.5% NaOH at 40°C for 10 minutes. The specimens were then rinsed in deionized water and dried in an oven at 60°C for 20 minutes. The second step was activation, which involved immersing the samples in a tin (II) chloride solution followed by a palladium (II) chloride solution for 10 minutes at room temperature. The samples were rinsed in deionized water again and then immersed in the electroless copper plating bath at 45°C for 20 minutes, with the pH value maintained at 12.75. The chemical composition of the plating bath is provided in Table 1.

Table 1 Electroless copper deposit method for MILIFE

Process	Chemicals and Processing Parameters	
1. Surface treatment	2.5% NaOH	40℃ 10min
2.Activation	1 g/100mL $SnCl_2$	Room temperature10min
	0.05g/100mL $PdCl_2$	Room temperature 10min
3. Deposition	6.5g/500mL $CuSO_4.5H_2O$ 10g/500mL EDTA·2Na 10g/500mL $KNaC_4H_4O_6·4H_2O$ 0.04g/500mL $K_4[Fe(CN)_6]·3H_2O$ 0.005g/500m 2’-2’-Bipyridine 7.5mL/500mL CH_2O	Sample- Solution ratio: 5g/500mL, pH 12.75 (NaOH 2.5g) ,45℃ 20min

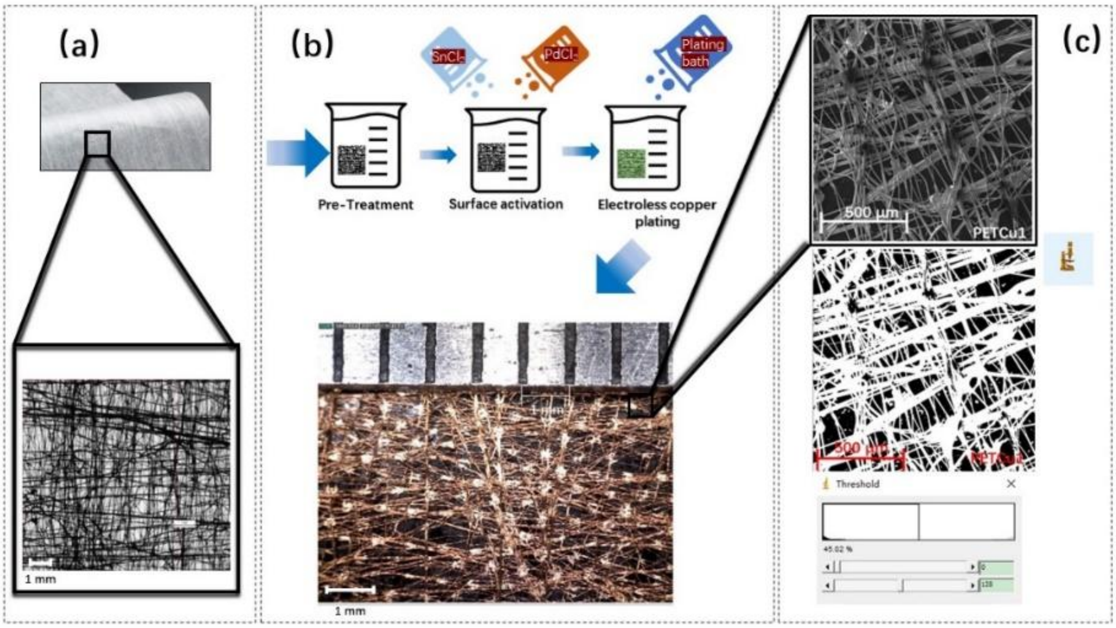


Figure 3 (a) Microstructure of greige nonwoven fabric (b) Electroless plating process and structure of copper coated fabric PETCu1. (c) Optical porosity calculation method via IMAGE J for sample PETCu1, First capture the original microscope picture from SEM, then convert the original picture into a binary picture. At last, adjusting the threshold until clearly identify the pores and calculating the area ratio

4.2 Morphological characteristics of copper particle deposited nonwovens

The geometrical characterization of copper-coated nonwoven and the purchased Meftex sample are listed in Table .2

Table 2 Geometrical characterization of Cu coated nonwoven PET and the purchased copper coated polyester nonwoven sample (Meftex)

Sample	Component	Usage	GSM (g/m^2)	Mass of Cu per unit area(g/m^2)	Thickness (mm)	Porosity (%)
PET (MILIFE)	Polyester nonwovens	1) EMI shielding mechanisem study 2)EMI shielding simulation verrification	10	0	0.068 ±0.002	82.31
PETCu1	Copper coated polyester nonwoven fabric		12.72	2.72	0.07 ±0.012	81.62
PETCu2			15.95	5.95	0.072 ±0.004	79.33
PETCu3			17.02	7.03	0.074 ±0.001	78.25
CuPET10	Purchased commercial Cu coated PETnonwovens	1) Mathmatical model verrification 2) Washing durabiltiy enhancement via Parylene-C treatment 3) Composites material development	11.84	1.8	0.042 ±0.003	79.57
CuPET20			24.01	4.01	0.1±0.002	77.5
CuPET30			41.67	11.67	0.13 ±0.004	75.9

The structure of Cu-coated PET nonwoven fabric PETCu1 can be observed in Figure 4(a). The fabric's fiber distribution is randomly displayed in vertical and horizontal directions. The greige fabric (MILIFE) is produced from the perpendicular arrangement of layers from theoretically parallel filaments with stable joining by point spots created by local melting. Different orientation (not regular net) is mainly due to inaccuracies of industrial fabrication. This structure and orientation of fibrous elements cannot be changed because of solid spots. The cross-section view can identify the coated copper particles covering the fiber. With the EDX analysis, the distribution of copper is presented in Figure 4(b). The relative weight ratio of Cu occupies value is increased with more copper content for the three samples (Fig. 4b). From the Cu distribution image, it was presented significantly that the deposited Cu was on the surface of the fibers.

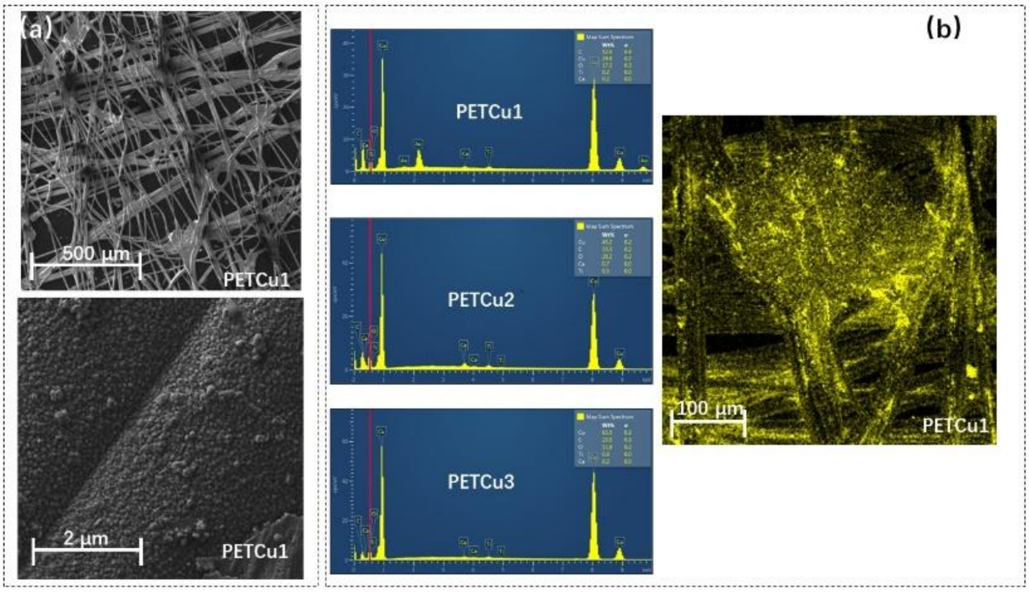


Figure 4. Morphological characterization of copper-coated PET nonwoven fabric of sample PETCu1 (a) Fabric structure of the fabric from the top view and cross-section direction obtained from SEM pictures. (b) Surface element analysis from Energy-dispersive X-ray spectroscopy of samples PETCu1

5. EMI shielding performance of copper-coated nonwovens and results analysis

The EMI shielding test results of the PETCu sample are presented in Figure 5(a). In the frequency range from 30 MHz to 3 GHz, it is evident that the SE performance of PETCu3 is the highest compared to the other two samples, with an average performance of 40.1 dB across the tested frequency band. To understand this result, several parameters influencing the EMI shielding performance of metallized textiles were studied based on related literature. Generally, three main factors determine the EMI shielding properties of a material: 1) Material conductivity and magnetic permeability, 2) Material porosity and pore shape, and 3) Material thickness.

For the PETCu sample, the variation in the amount of plated copper particles resulted in changes in porosity and conductivity. It is important to note that the sample's thickness also varied, which in turn affected conductivity. In this case, the synchronous changes in thickness and conductivity were caused by different amounts of plated copper particles. Figure 5(b) and 5(c) illustrate the relationship between optical porosity, the relative weight of copper in the samples, and EMI shielding effectiveness at 1.5 GHz. The results show that a decrease in optical porosity significantly enhances EMI shielding effectiveness, and an increase in the mass of copper particles also improves SE. This conclusion is consistent with the findings of other studies on the electromagnetic shielding effectiveness of metallized textiles[52,53].

For different applications of EMI shielding materials, the weight of the electromagnetic shield material is also significant. In these cases, the specific electromagnetic shielding effectiveness based on planar density, SEG [dB·m²/g], can be calculated using the following equation (8).

$$SEG = \frac{SE}{w} \quad (8)$$

where w [g/m^2] is the planar density.

A material with a higher SEG is desirable, as it indicates a lower weight and relatively higher SE. While increasing the shield's thickness can enhance its shielding ability, the resulting weight increase may negatively impact the application of this metallized textile for EMI shielding. Researcher S. Palanisamy compared the EMI shielding performance of 35 different metallized textiles. According to his research, optimizing both the weight and shielding effectiveness is crucial for the practical application of these materials.[54]. The SEG of PETCu was also calculated and compared with Palanisamy's results. As shown in Figure 5(d), the PETCu samples were in a leading position compared to other fabrics in terms of relative weight electromagnetic shielding performance. The SEG value of PETCu ranged from 2 to 2.52, whereas other metallized or carbon-based textiles had SEG values ranging only from 0.03 to 1.04. The relatively lower weight and higher SE of the PETCu samples offer greater potential for electromagnetic shielding applications.

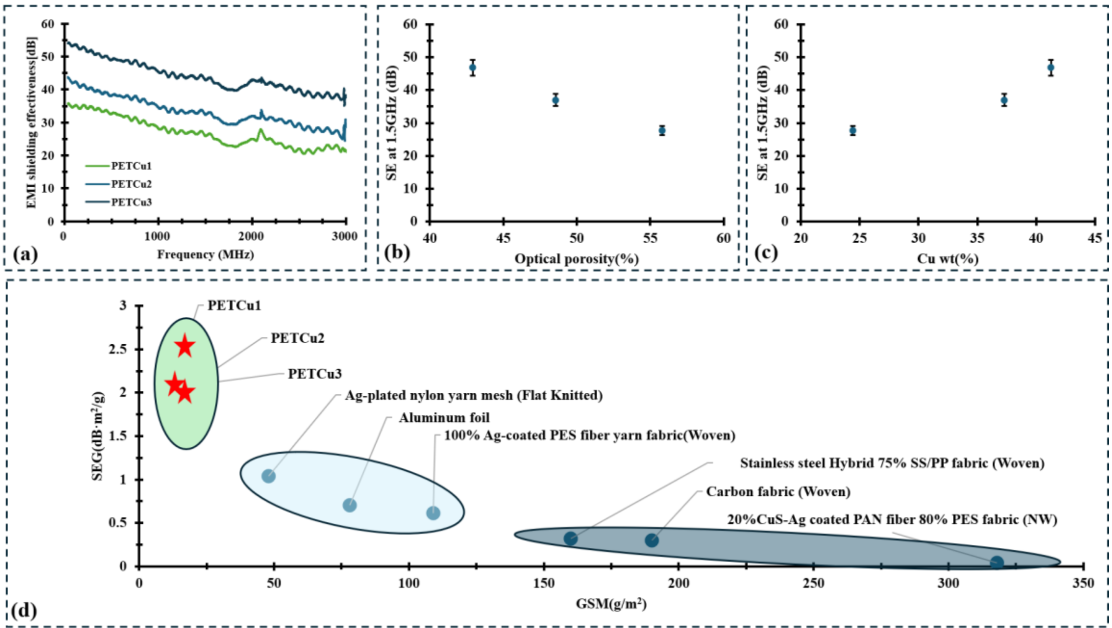


Figure 5. (a) EMI shielding test results of PETCu1, PETCu2, PETCu3 (b) Relationship between optical porosity and SE at 1.5GHz (c) Relationship between relative copper weight of the sample and SE at 1.5GHz (d) Relative SE according to planner density performance compared with other metalized textiles

For the case of multilayer CuPET samples, the SE at 1.5 GHz is all above 40 dB, which is classified as an excellent category for professional use. The maximum SE at 1.5GHz can be reached at 87.14 dB by five layers of CuPET 20. This performance can be classified as an "excellent" grade[55]. Depending on the results, from 1 layer to 2 layers, the SE increase rate compared to the previous layer is from 18.91% to 31.26%, 2 layers to 3 layers are between 3.37% and 15.98%, from 3 layers to 4 layers is 2.67%-43.64%. However, the increasing rate from the 4th layer to the 5th layer is only 0.37%-2.47%(Figure.6a).

For multilayer structured CuPET, the reflection loss SE_R is relatively constant compared to a single layer. When the layer is increasing, the absorbing loss SE_A is increasing due to the change in thickness. According to the further research results, it can be clearly identified that the multilayer structure enhanced the internal multireflection attenuation inside the material. On the other hand, the transmitted EM wave will decrease due to the decreasing porosity. When the thickness increases from the fourth layer to the fifth layer, the number of porous which electromagnetic waves can penetrate has been reduced to a minimal extent. Therefore, when the number of layers increases, the increase rate of the shielding effectiveness compared to the previous layer will decrease.

A higher mass per unit area fabric (CuPET30) may perform better SE in this research. However, on the same SE level, the lower mass per unit area fabric (CuPET10) shows better air permeability. Considering the balance of SE and air permeability for CuPET (Figure 6b). 3-4 layers of CuPET 10 will perform average SE from 59.79 dB -78.38 dB in the frequency band 30 MHz to 1.5 GHz, and air permeability from 2942 l/m^2/s-3658 l/m^2/s.

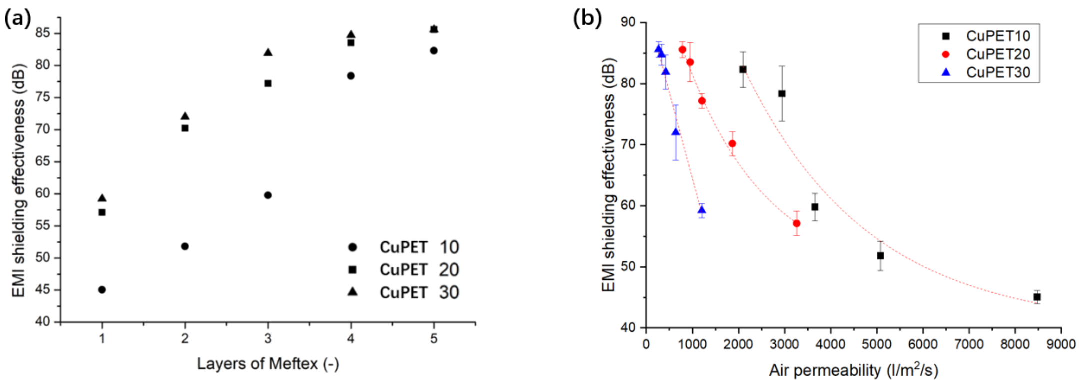


Figure 6 (a) EMI shielding effectiveness (EMSE) of increasing layers for CuPET samples (b) the air permeability changed with increased layer of CuPET

To compare the EMI shielding effectiveness of multilayered CuPET samples with other referenced sample, the value of shielding effectiveness in unit thickness (dB/mm) was calculated (Figure 7). From the result, it clearly to see that the CuPET samples were placed in the leading place compared to other EMI shielding textiles[50,54,56].

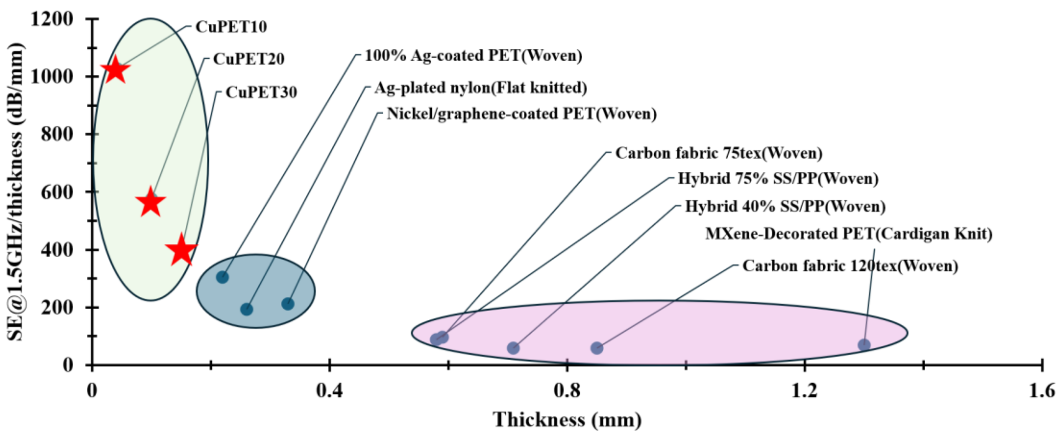


Figure 7 Comparison of the value of SE at 1.5GHz/thickness(dB/mm) from CuPET samples and referenced metalized EMI shielding textiles

6. EMI shielding simulation development for metalized thin nonwovens

The simulation environment was established based on the waveguide method, specifically in the TE10 mode. Employing the finite element method (FEM), the ANSYS HFFS software environment was utilized to generate simulated results of the shielding effectiveness, presented in the form of transmittance coefficients. The virtual measurement environment was created within Ansys HFSS, replicating the geometry of the physical measurement setup. The measurement stand consisted of waveguides that corresponded to the recommended frequency ranges: WR-1500 (500-750 MHz); WR-975 (750-1150 MHz); WR-650 (1150-1500 MHz)

In Figure 8, the EMI shielding simulation environment was presented. Within the waveguide structure, an optimized model of the test sample was positioned. The decision to employ an optimized module, as opposed to the textile's original geometrical model, was primarily driven by the significant time and computational resources required to run the original textile geometrical model. Importing the complete mesoscale textile geometry directly into the simulation environment would risk system crashes, particularly during the meshing process. The intricate and complex nature of textile structures, compared to other engineering objects, demands substantial computational power to mesh all the fibers or yarns within a fabric. Consequently, the use of an optimized textile model is crucial for conducting the EMI simulation.

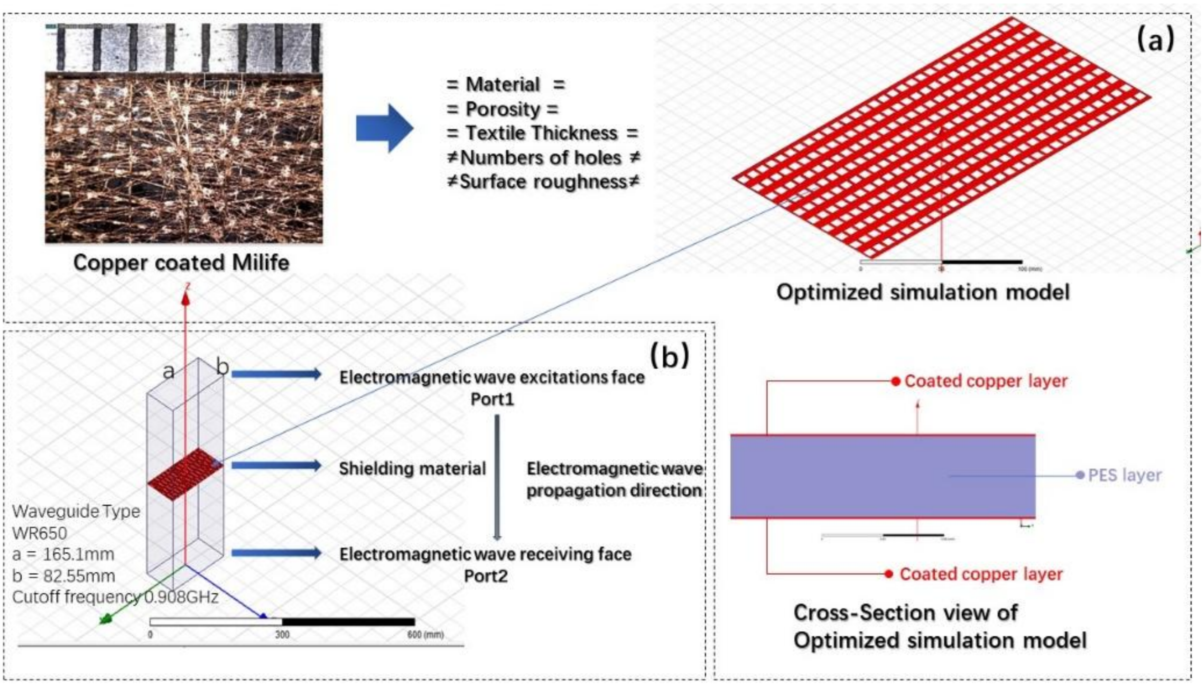


Figure 8 Waveguide model building in ANSYS HFSS (a) Optimized textile model for the simulation environment and cross-section view of this model (b) WR650 Waveguide mode for EMI shielding simulation

Figure 9 show the copper-coated samples measured and simulated EMI shielding effectiveness. The measured results from 0.5GHz to 1.5GHz are constantly exported from the network analyzer. The simulated result presents inconstantly due to the results were combined three types of the waveguide. Obviously, with the increased copper content from PETCu1 to PETCu3, the SE performance is improved from both measured and simulated results. Due to the limitation of the waveguide model, the simulated value performs discontinuity at the boundary frequency point. The simulated results perform relatively good arrangement with the measured value. When the sample's SE is over 35dB, this mode faithfully represents the measured results in the frequency ranges from 0.5GHz to 1.5GHz. The compatibility is slightly worse for the sample's SE, around 30dB, but the error does not exceed 5 dB. Due to the limitation of the waveguide model, the simulated value performs discontinuity at the boundary frequency point. The simulated results perform relatively good arrangement with the measured value. When the sample's SE is over 35dB, this mode faithfully represents the measured results in the frequency ranges from 0.5GHz to 1.5GHz. The compatibility is slightly worse for the sample's SE, around 30dB, but the error does not exceed 5 dB. To evaluate the results of these three samples, the SE obtained at 1.5 GHz frequency was recommended 33. This frequency was significant because it is close to the frequency running by many working devices (e.g., cell phones, GPS, and Wi-Fi routers) 33. Figure 6(d) presented that simulated values are very close to the experiment results at 1.5GHz, especially for PETCu2 and PETCu3.

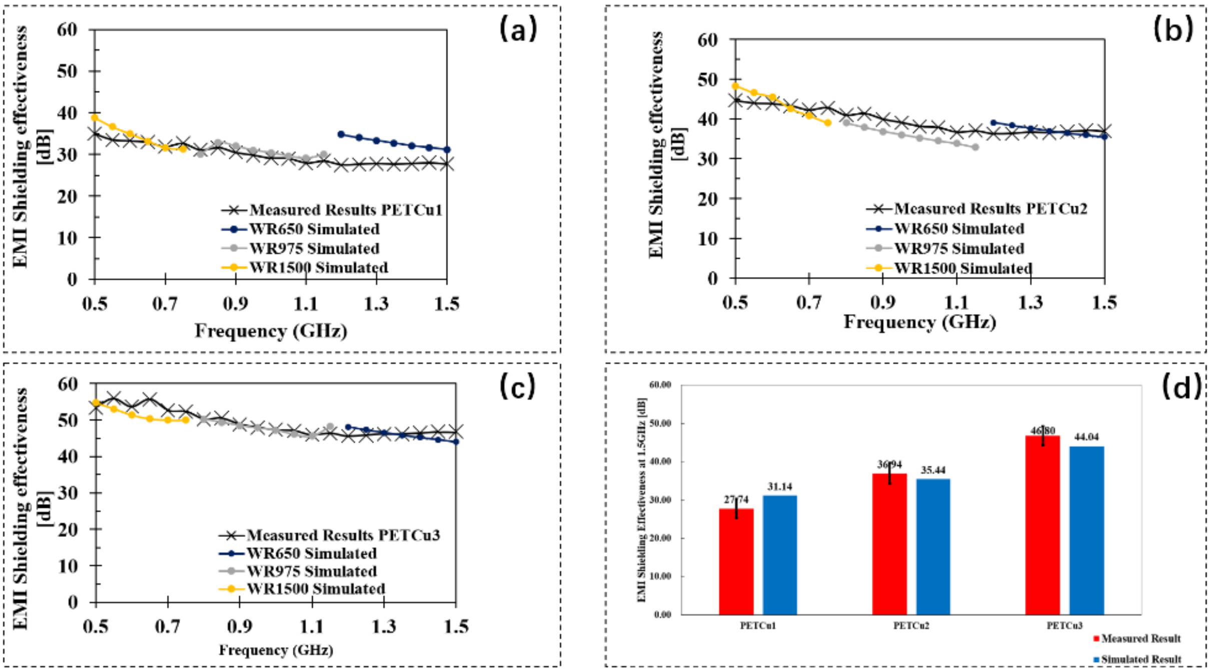


Figure 9 Results of measurements and simulated SE in the tested frequency range from0.5 to 1.5 GHz for textile samples (a) PETCu1 (b) PETCu2 (c) PETCu3 (d) results of measurements and simulated SE in the tested frequency 1.5 GHz for textile samples

To evaluate whether the average difference between the simulated and measured result is significant or caused by random error, a statistical analysis using a two-sample t-test is performed. The significance level α=0.05, and each result from the simulated and measured groups on the same frequency point is compared. The null hypothesis is given as:

$$H_0: \mu_s=\mu_m$$

This hypothesis means the mean value of SE calculated by simulation method μ_s is equal to that of SE measured by the coaxial transmission line method μm.
The alternative hypothesis is defined as:

$$H_1: \mu_s \neq \mu_m$$

The p-value of the t-test is listed in Table 3

Table 3 p-value of two-sample t-test for simulated SE value and measured SE value

	PETCu1	PETCu2	PETCu3
The p-value of two-sample t-test	0.001	0.738	0.392

The t-test result presented a significant difference between the mean value of measured and simulated SE for the sample PETCu1, which p-value is less than 0.05. For samples PETCu2 and PETCu3, the t-test confirms no significant difference between the measured and simulated results, with a p-value of more than 0.05. This conclusion presented that the simulated results from PETCu2 and PETCu3 perform better compatibility with experimentally measured results.

Table 4 compared the published solutions of EMI shielding for conductive material. For simulation run, the level of detail in the model to some extent affects the final simulation results. Considering the textile structure, the macro scale will process the fabrics as plain board, mesoscale textiles will presenting the porous structure, the microscale should able to identify to the fiber level of the fabric. From the listed solutions, there is no solution processing the model into microscale, which is understandable considering the balance between simulation run time and calculation costs. However, from the listed solutions, there is no available solution for EMI shielding simulation run for metalized nonwoven fabrics. In these points, this newly developed method filled the blank for EMI shielding simulation of metalized textiles.

Table 4 Comparison of newly developed solution with existing simulation solutions

EMI shielding simulation solutions	Software	Scale of Modeling	Suitable for metlaized nonwoven
Full-Wave modeling of screen printed EMI shield[57]	CST	Yarn	Not discussed
FSFs with cross-shaped units EMI shielding simulation[58]	HFSS	Yarn	Not suitable
Simulation analysis for electromagnetic shielding of certain type chassis [59]	CST	Fabric	Not suitable
EMI shielding for conductive woven fabrics[47]	HFSS	Fabric	Not discussed
Own solution	**HFSS**	**Yarn**	**Suitable**

7. Geometrical modeling for the fiber irregular oriented thin and porous nonwoven

In this section and following chapters, considering the requested size of sample and ensure the better homogeneity of the material, in this study, the copper-coated nonwoven fabric, "Meftex" series sample were chosen as the sample for geometrical modelling, mathematical modeling and further development.

For development of fiber-level geometrical model of non-woven microstructure, some data about its orientation and distribution must be known. The structure of CuPET is different compared to other non-woven fabrics. There are weft-yarn-like horizontal fiber and warp-yarn-like vertical fiber. The fabrics are constructed from these two systems fibers by hot bending process. Generally, all fiber is straight, but the degree of inclination of the fiber is random concerning the horizontal and normal, which is the character of non-woven fabrics. In this case, the geometrical model should be constructed by straight lines with random slop (the range of random slop is determined by the next step) plus the boundary conditions defined by the module's width and length.

The model is implemented as parametric script in Python, so that the length, angle and variations in the distributions can be parametrically changed. Finally, the python script generated axes are exported into open csv-based format for 3D visualization with the TexMind Viewer. The generated non-woven fabric module was compared with the scanning electron microscope picture of the non-woven fabric at the level of qualitatively and quantitatively (Figure 10a). The comparison of the optical porosity of the modelled and microscopic picture demonstrates very close results. The optical porosity of the sample's SEM picture is 45.01%, and for the model, the optical porosity is 44.55%. The generated model matches the actual sample structure (Figure 10b).

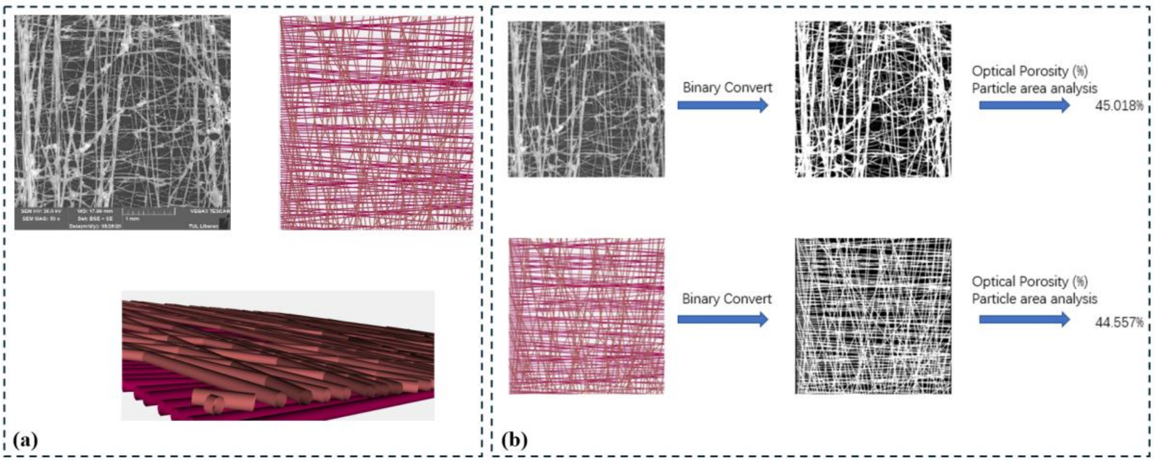
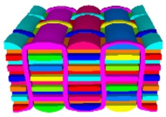
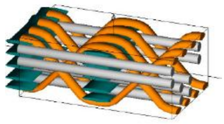
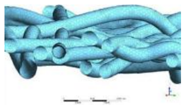


Figure 10 (a) Generated 3D geometric module and the cross-section view (b) Optical porosity test result compare with SEM scanned picture and developed 3D geometrical model

Among the existing modeling methods, including those provided by commercial software, there are not many parametric modeling options for thin nonwovens. Most existing methods are primarily aimed at more structurally regular textiles, including woven fabrics, knitted fabrics, and thicker nonwovens. By using Python scripts in conjunction with Texmind software, it is possible to achieve precise control of nonwoven parameters that other software cannot provide. The comparison of various methods is shown in the table below.

Table 5 Comparison of newly developed software model with other existing textile geometrical software models

Software	Minimal Scale of Modeling	Suitable for nonwoven	Model Example
TexGen[60]	Yarn	Not suitable	
WiseTex[61]	Yarn	Not suitable	
Solidworks[62]	Fiber	Suitable but complex	
Texmind[63]	**Fiber**	**Suitable**	

8. Mathematical modeling for predicting the SE for metalized nonwoven fabric

The complete modeling methodology and processes were presented in the attached published paper. After sufficient literature review, the existed EMI shielding mathematical models were most developed for woven based textile (Equations 1-7). Obviously, by using the existing models to calculate the SE of nonwoven based EMI shielding material cannot reach correctly result and there was barely any mathematical model developed for thin metalized nonwoven materials (Figure 11a). The main reason is that due to the non-uniform pore size distribution of nonwovens, it is very difficult to select the parameters of the pore size in the model. In this case, the equivalent transformation of nonwoven structure into woven fabric structure and optimization of the existing model can be used as a basic method for EMI shielding mathematical modeling of metallized nonwoven. To confirm this hypothesis, the optimized textile model was imported into simulation environment. The result showed that it's possible to predict the EMI shielding performance of nonwoven textiles after converting the nonwoven structure into woven structure without changing the volume porosity, thickness of the material and conductivity. As the hypothesis was proved, the finalized mathematical model for nonwoven based EMI shielding material was proposed after optimizing the existed model (Equations 9-11). The SI units are used in all formulas, the unit of some key parameters for mathematical model was marked. The newly developed mathematical prediction model in this paper for prediction the EMI shielding of metalized nonwoven fabric are presented in the following:

$$l = \sqrt{2} \cdot \sqrt{\frac{V_{pore}}{n_{cal} \cdot t}} \tag{9}$$

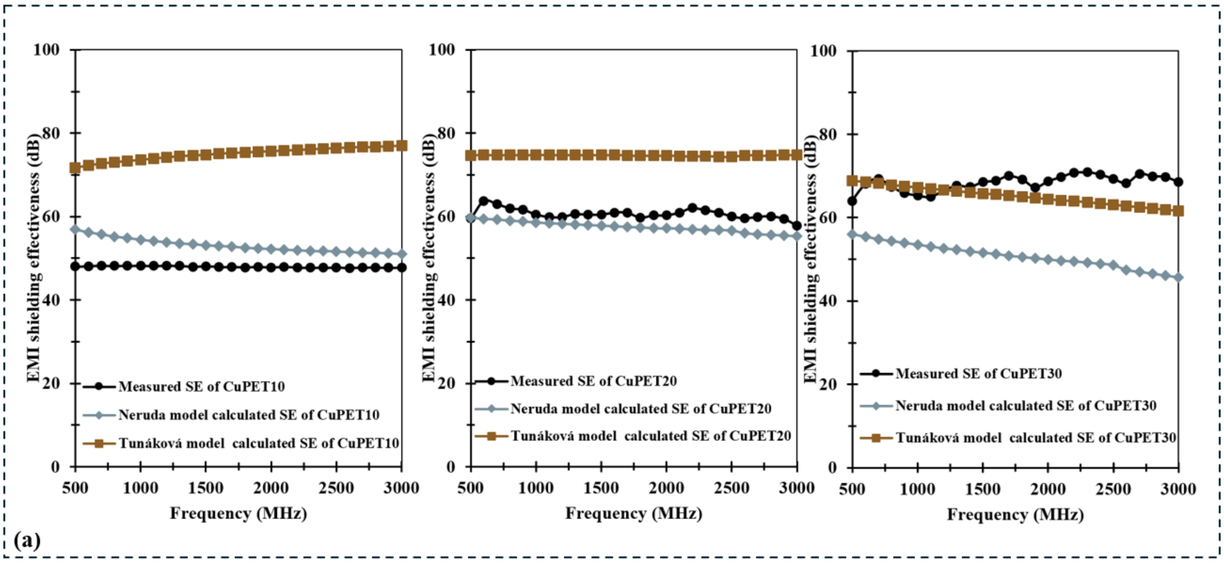
$$SE_{foil} = 156.78 + 20 \cdot \log\left(\sqrt{\frac{K_r}{f\mu_r}}\right) + 8.6859 * \frac{t}{K} + 20 \cdot \log\left(1 - e^{\left(\frac{-2t}{\delta}\right)}\right) + 5328.3 \cdot K \; (t \leq \delta) \tag{10}$$

$$SE_{foil} = 156.78 + 20 \cdot \log\left(\sqrt{\frac{K_r}{f\mu_r}}\right) + 8.6859 * \frac{t}{K} + 5328.3 \cdot K \; (t > \delta) \tag{11}$$

It should be noticed that generally the mathematical model used to predict the SE are empirical model, not physical model because there is not dimensional homogeneity of the equations. The detailed derivation of the mathematical model please refer A4.

It's clearly to see that for sample CuPET20 and CuPET30 the majority part of measured value curve was in the model predicted field, and the model calculated average SE presented good agreement with the measured value (Figure 11b). For CuPET10 between 500MHz to 1500MHz the model predict field can cover the measured value, from 1500MHz to 3000MHz the measured value curve is over prediction field and close to the upper limit line. For the reason given above, due to the low thickness of CuPET10, the multireflection effect in the material should be considered. In practice there is a high impact on multireflection attenuation from thickness, pore morphology and surface area. With this mathematical mode, it's very limited consider all these parameters in the multireflection part of calculation, that caused the inaccurate to predict the attenuation with multireflection case.

By combine the existing models and new developed modes, in Figure11(c) the comparison of model calculated and measured values of EMSE for all samples at 1500MHz (1.5GHz). This frequency was analyzed because this frequency is close to the working frequencies of electric devices, for example Global System for Mobile Communications (GSM) support the 1800MHz band. The result shows good agreement from measured and model calculated values, there is no mathematical significant difference from these two values.



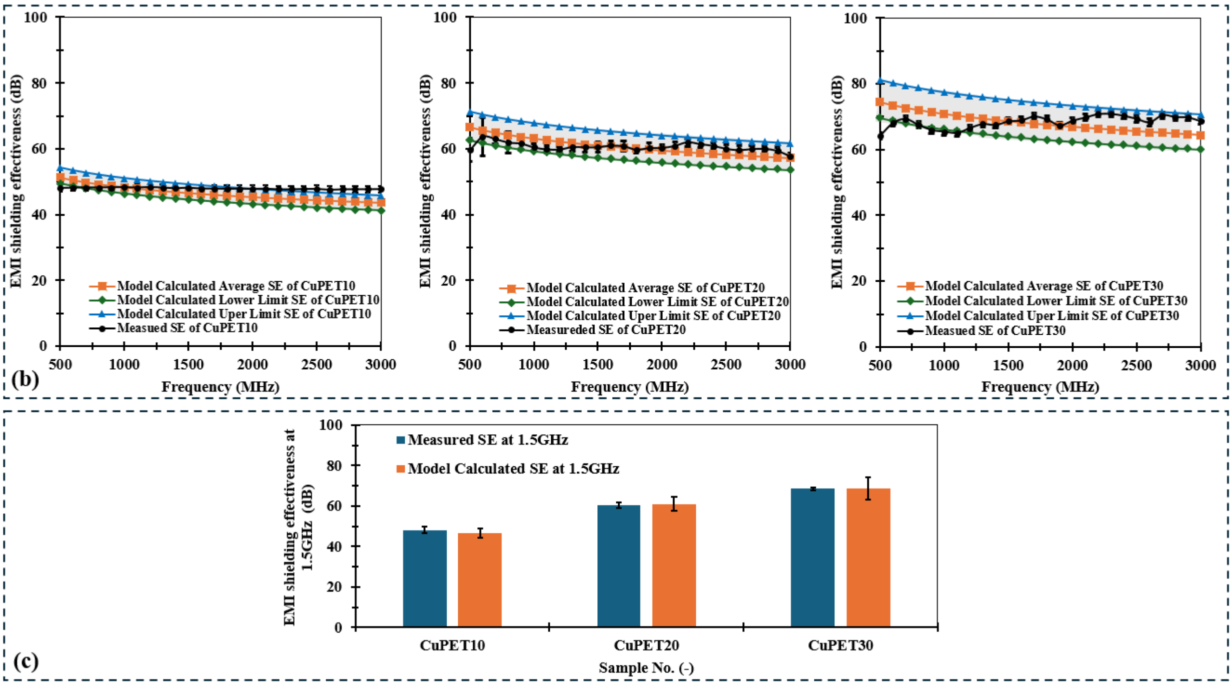


Figure 11 (a) Comparison between existing SE prediction mathematical model to measured SE of thin metalized nonwoven (b) Frequency dependence EMI shielding effectiveness of model predict value and measured value from sample CuPET10, CuPET20, CuPET30 (c) Comparison between predict SE value and measured value at 1.5GHz for each sample.

To judge whether the average difference between the model calculated and measured result is significant or caused by random error, the statistical analysis method of two-sample t-test was performed. (The method description is in chapter 6.)

The p-value of this t-test is listed in Table 6.

Table 6 p-value of two-sample t-test for calculated SE value and measured SE value.

Sample No.	p value from two sample t-test
CuPET10	0.0002
CuPET20	0.56
CuPET30	0.66

The t-test result presented a significant difference between the mean value of measured and model calculated SE for the sample CuPET10, which p-value is less than 0.05. For samples CuPET20 and CuPET30, the t-test confirms no significant difference between the measured and simulated results, with a p-value of more than 0.05. This conclusion matches the results from Figure 11(b) that the simulated results from CuPET20 and CuPET30 perform better compatibility with experimentally measured results.

9. Washing durability enhancement for metal particles surface coated textiles with good air permeability

The Parylene CVD processing was performed by the Parylene Deposition System (SCS PDS2010) located in CEITEC, Czech Republic. The CuPET sample was cut in the size of 13cm*13cm, which matching the size of the sample holder in SCS PDS2010. After 24 hours of conditioning in room circumstances, the Cu/PET was placed on a homemade supporting frame made from paper for a complete and uniform coating. The following Figure12 presents the deposition process. The addition of Parylene-C dimer was controlled differently as 2 g, 6 g, 10 g, and 15g for one deposition on the fabric size of 13 cm*13 cm. For brevity, the final Parylene-C encapsulated copper-coated sample was named Py2/Cu/PET, Py6/Cu/PET, Py10/Cu/PET, and Py15/Cu/PET according to the amount of Parylene-C used in this encapsulation process. Due to the size of the CuPET and limited volume, it does not mean after adding 2 g Parylene-C in the deposition machine then the sample will gain 2 g mass after coating process. In the size of 13 cm*13 cm sample, the mass is increased only 0.078 g after adding 2g Parylene-C in the deposition system. Same for the 6 g, 10 g, 15 g samples. The geometrical characterization of Parylene-C encapsulated sample Py/Cu/PET are listed in Table 7. The optical porosity is based on selected threshold, specify conditions of its evaluation. Volume porosity is calculated and it is necessary to briefly specify evaluation of gsm, fiber density and thickness.

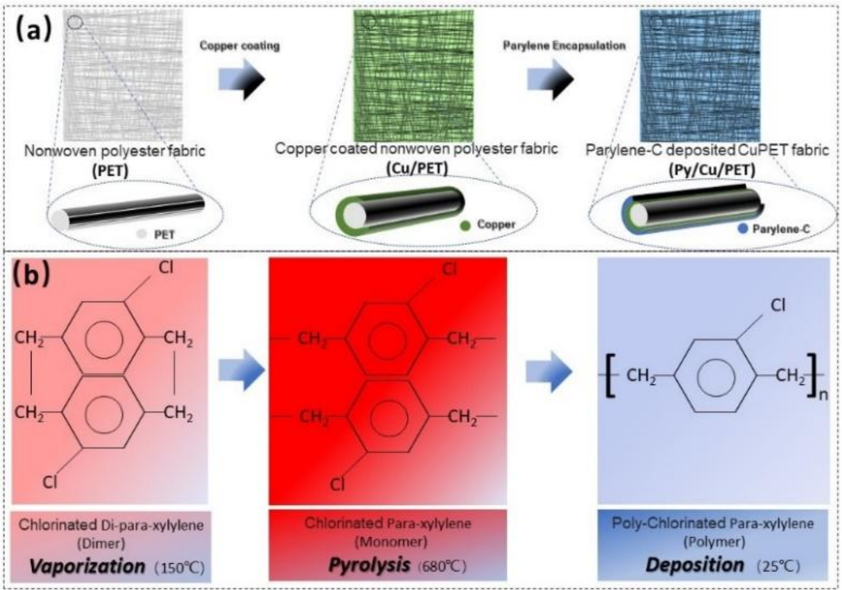


Figure 12 A schematic illustration of the fabrication process. (a) Py/Cu/PET preparation process and sample simulation photo. The insert fiber picture displays the feature of different material layer structures after Parylene encapsulation (b) The Parylene deposition process on Cu/PET.

Table 7 Geometrical characterization of Py/Cu/PET

Sample Number	Sample thickness (mm)	Optical Porosity (%)	Volume Porosity (%)	Calculated Parylene-C film thickness(μm)
Py2/Cu/PET	0.057±0.007	30.846	78.69	15
Py6/Cu/PET	0.076±0.008	23.192	73.04	34
Py10/Cu/PET	0.092±0.008	19.386	71.11	50
Py15/Cu/PET	0.134±0.010	16.262	68.53	90

The SEM image of the CuPET shows good porosity (Figure 13a). It can be observed that the copper particles distributed evenly on the surface of the fiber (Figure 13b). During the Parylene encapsulating process, the gaseous monomers of Parylene-C were evenly distributed into the whole chamber under vacuum circumstance. Unlike traditional coating technology that blocks the pores of the fabric, the monomers of Parylene-C were able to penetrate the apertures of the Cu/PET and deposit on the fiber surface evenly under ubiquitous gas-phase deposition at the molecular level. As a result, the apertures will not be blocked, which can maintain the good air permeability of the sample (Figure 13c). On the surface of the fiber, the Parylene-C forms a dense film in 3D structure rather than two simple layers covering only on the top and bottom of the fabric surfaces. Such hierarchical structure enables the highly pervasive protection for the copper particles interconnector by Parylene-C (Figure 13d).

Depending on the Cl element in the molecular structure of Parylene-C, the Cl element can be the identity of the existing Parylene-C film. By using EDS analysis, the untreated Cu/PET demonstrated that the copper particles were evenly distributed on the surface of the sample (Figure 13e). After the deposition process, the EDS map shows the Cl element evenly spread on the treated sample Py15/CuPET (Figure 13f). On the focus of fiber level, the element Cl concentrated on the surface of the fiber. Cu element was evenly distributed on the fiber surface. This EDS map illustrates that after the encapsulating process, the Parylene-C film coved the copper particles on the CuPET surface perfectly (Figure 13g).

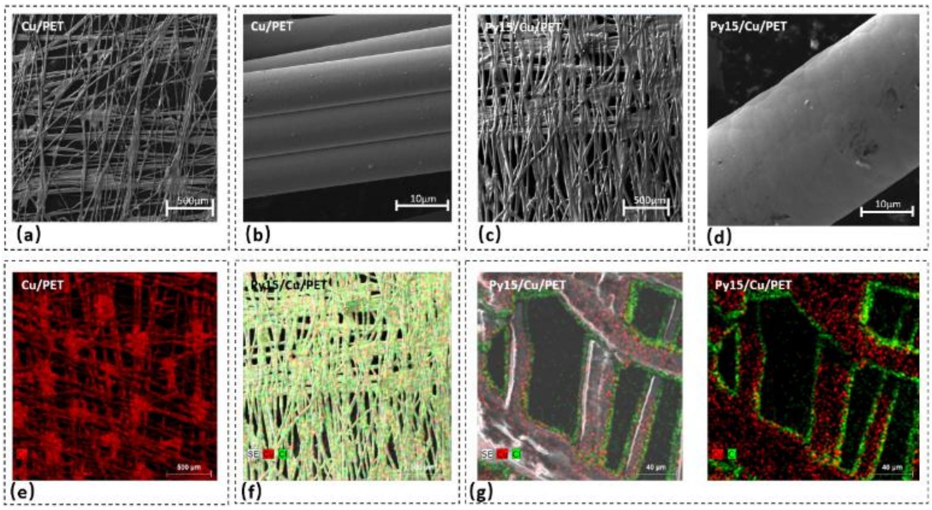


Figure 13 Morphology and physical characterization of Cu/PET and Py/Cu/PET (a)SEM scanned picture of Cu/PET (b)SEM scanned picture of Cu/PET focus on the copper particle on the fiber surface. (c) SEM scanned picture of Py15/Cu/PET (d) SEM scanned picture of Py15/Cu/PET focus on the Parylene film coated on the fiber surface. (e) EDS mapping of element Cu on the surface of Cu/PET. (f) EDS mapping of element Cu and element Cl on the surface of Py/Cu/PET. (g) EDS mapping of element Cu and Cl on the fiber of Py15/Cu/PET

The Parylene-C encapsulated fabric demonstrates enhanced machine-washing durability with the increased amount used in the deposition process. Using 2 g Parylene-C for deposition was not enough for ten machine washing cycles. With the increasing used amount of the Parylene-C, the EMI shielding property was gradually improved from 12.76 dB to 26.6 dB via integrating increased Parylene-C from 6 g to 15 g (Figure 14c). The best machine-washing ability regarding EMI shielding performance compared to other samples was Py15/Cu/PET. The average SE between frequency band from 30 MHz to 3 GHz remains 27.5 dB after ten times machine washing cycle (Figure 14c-d). The SE loss at 1.5

GHz after the machine-washing cycle can be observed in Fig 3g. For Cu/PET, the SE loss at 1.5 GHz reaches 99.5%. The improvement was significant with processing 15 g Parylene-C, and the SE loss at 1.5 GHz was 35.9%.

For Cu/PET after the hand washing cycle, the SE dropped significantly (Figure 14e). For the first three hand washing cycle, the SE dropped around 10 dB after one hand washing cycle. After ten hand washing cycles, the SE at 1.5 GHz was 1.3 dB, which lost 97.19% of EMI shielding property. Similar to the machine-washing cycle results, the Py/Cu/PET samples perform enhanced hand washing with the increased amount of Parylene-C implemented in the deposition process. After increasing the encapsulated amount of the Parylene-C, the SE loss at 1.5 GHz was gradually reduced from 57.5% to 12.9% via integrating increased Parylene-C from 6 g to 15 g(Figure 14f-g). The best hand-washing ability regarding EMI shielding performance compared to other samples was Py15/Cu/PET. The average SE between the frequency band from 30 MHz to 3GHz remains 39.93 dB after ten times hand washing cycles, which dropped around 17.66% compared to the unwashed sample (Figure 14h).

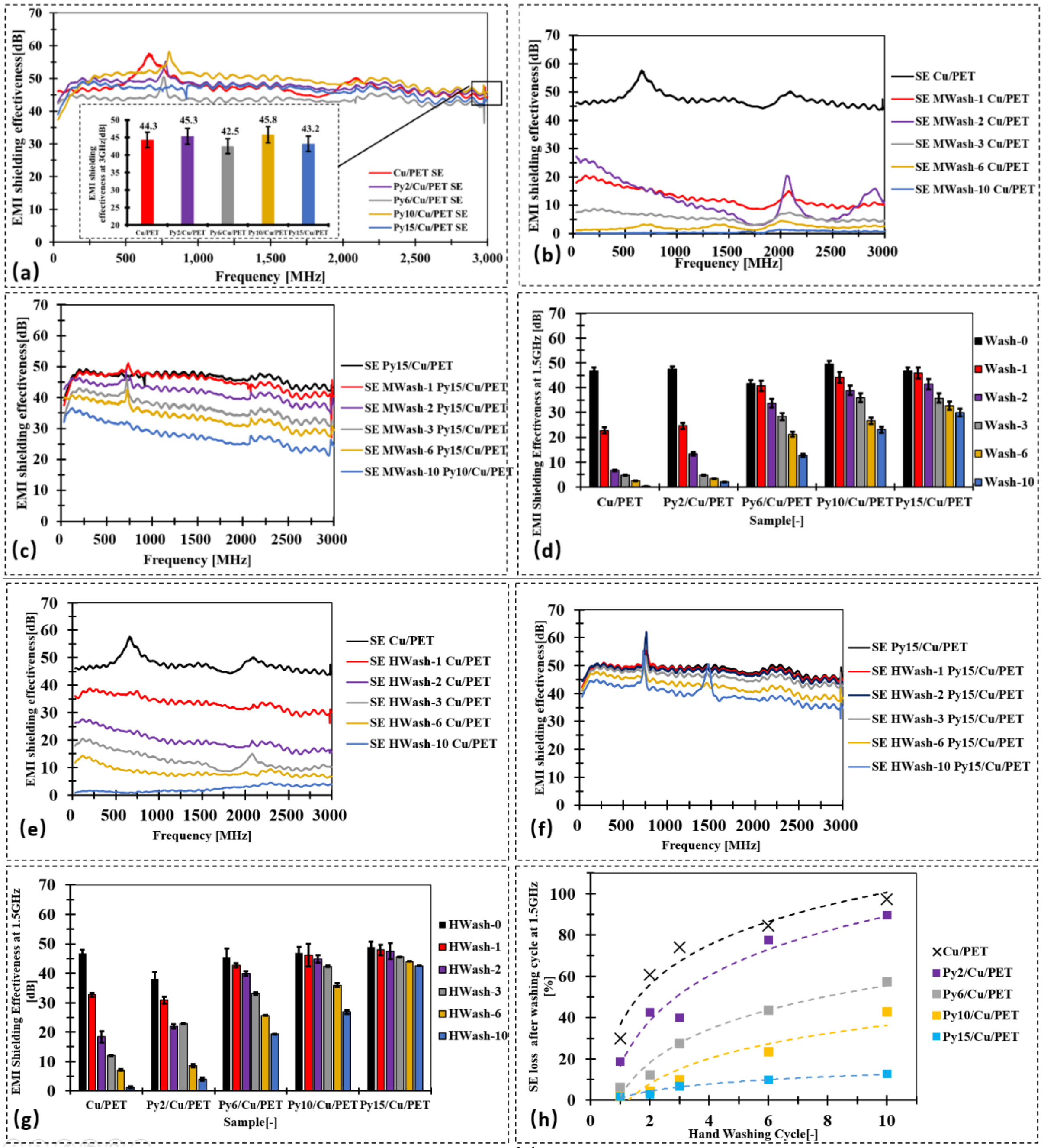


Figure 14 EMI shielding after machine/hand washing (MWash) cycle (a)EMI shielding effectiveness of Cu/PET and Py/Cu/PET (b) SE of Cu/PET with ten machine washing cycle (c) SE of Py15/Cu/PET with ten machine washing cycle (d) SE at 1.5GHz compared with Cu/PET and Py/Cu/PET after ten machine washing cycle (e) SE of Cu/PET with ten hand washing cycle (f) SE of Py15/Cu/PET with ten hand washing cycle (g) SE at 1.5GHz compared with Cu/PET and Py/Cu/PET after ten hand washing cycle (h) SE loss at 1.5GHz for Cu/PET and Py/Cu/PET after ten hands washing cycle.

Figure 15a presents the air permeability of Cu/PET and Py/Cu/PET before and after the washing cycle. As referred to in the geometrical structure of Py/Cu/PET, due to the CVD method, the Parylene-C film covered the fiber surface without blocking all the fabric apertures, which enabled the fabric to maintain good air permeability. The Parylene-C film increased the fiber diameter, leading to the pore size decrease. Such changes affect the air permeability of the fabric to some extent. With the increase of Parylene-C to 15 g, the air permeability was reduced from 3930 mm/s (Cu/PET) to 1043.6mm/s (Py15/Cu/PET). The reduction of the fabric porosity causes this change. The increasing deposited Parylene-C made the fiber diameter thicker, which caused the synchronized drop in fabric porosity and air permeability (Figure 15b).

Compare with other metalized textiles and normal clothing used fabrics, the Py/Cu/PET samples presented excellent air permeability[64–67]. The compared results were showed in Figure 16. From this result, it's clearly illustrated that comparing with other metalized textiles or normal clothing used textiles, the Py/Cu/PET series samples presented good washable durability, at the same time maintained excellent air permeability. Parylene encapsulation also brings excellent acid and alkali corrosion resistance, anti-friction performance, the detailed analysis was described in A5.

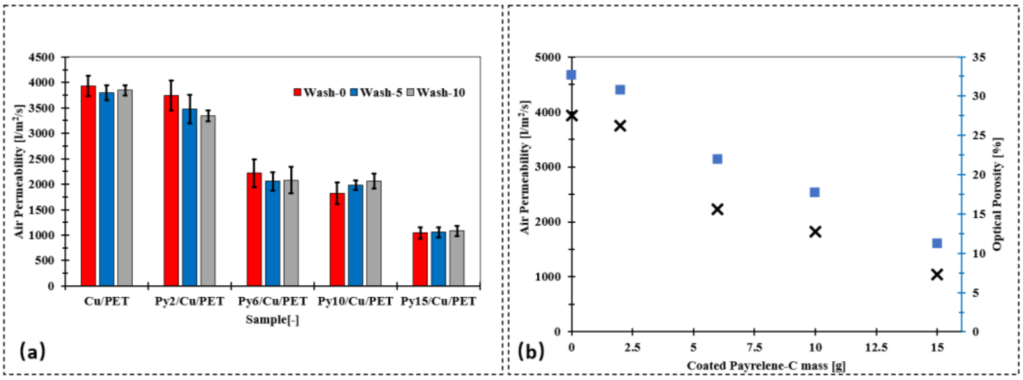


Figure 15 (a) Comparison of air permeability for Cu/PET and Py/Cu/PET before and after the washing cycle. (b) The relationship between air permeability and optical porosity with different coated Parylene-C. (c) TG and DTG test results of Cu/PET and Py15/Cu/PET.

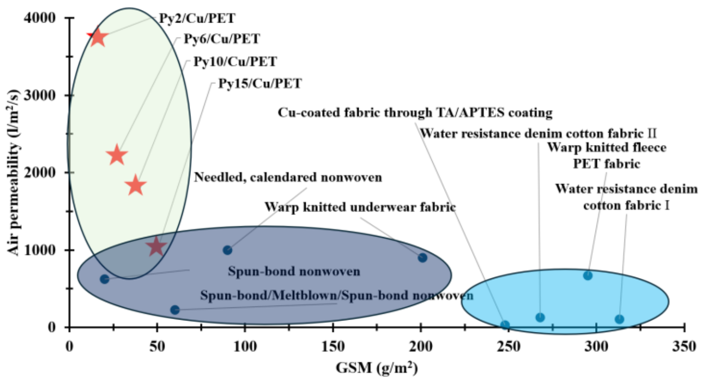


Figure 16 Comparison of the air permeability with other metalized textiles and clothing used textiles

10. Conclusion

This dissertation serves as a comprehensive summary of my published scientific journal articles, in which I am the first author related to the PhD thesis topic. All the journals have an impact factor and are listed in the Journal Citation Reports, with quartile rankings in Q1 or Q2. The research conducted for my Ph. D work was approached systematically, both theoretically and practically. This work addresses gaps in several research areas of EMI shielding textiles, with a particular focus on metal particles surface coated nonwoven textiles. Through the research of this paper, the following issues concerning the electromagnetic shielding effectiveness of metal particles surface coated textiles were solved:

- Development of copper coated thin nonwoven fabrics. By testing the electromagnetic shielding effectiveness and other related properties of copper-plated nonwovens, it was found that using a multi-level structure effectively enhances the attenuation of electromagnetic waves through multi-layer reflection within the material, thereby improving the overall electromagnetic shielding effectiveness. Despite the increased thickness reducing breathability, the excellent air permeability of the greige nonwoven fabrics allows them to maintain superior breathability even after stacking three layers. This stacking also provides an enhanced EMI shielding effect.
- Creation of physical model and simulation tools for characterization metal particles surface coated nonwovens. This model was successfully simulated in the waveguide electromagnetic shielding effectiveness simulation environment of Ansys HFSS. Additionally, based on the concept of equivalent model conversion within the simulation environment, the mathematical model for predicting the electromagnetic shielding effectiveness of metal particles surface coated nonwovens was successfully optimized.
- Enhancing the machine/hand wash resistance and mechanical properties of existing electromagnetic shielding fabrics wider the potential for using electromagnetic shielding textiles in clothing or other harsh environments. This work successfully applied a Parylene encapsulation on the surface of metal particles surface coated fibers through chemical vapor deposition, which significantly enhanced the water wash resistance of the fabric. Additionally, due to Parylene's excellent chemical corrosion resistance and wear resistance, the encapsulated electromagnetic shielding textiles exhibit these superior properties as well.

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12. List of publication by author

12.1 Journal articles

1. **Hu, S**.; Wang, D.; Periyasamy, A.P.; Kremenakova, D.; Militky, J.; Tunak, M. Ultrathin Multilayer Textile Structure with Enhanced EMI Shielding and Air Permeable Properties. Polymers 2021, 13, 4176. https://doi.org/10.3390/polym13234176 **(Q1, IF:5)**
2. **Hu S**, Wang D, Kyosev Y, et al. The novel approach of EMI shielding simulation for metal coated nonwoven textiles with optimized textile module[J]. Polymer Testing, 2022, 114: 107706. **(Q1, IF:5.1)**
3. **Hu S**, Wang D, Křemenáková D, Militký J. Washable and breathable ultrathin copper-coated nonwoven polyethylene terephthalate (PET) fabric with chlorinated poly-para-xylylene (parylene-C) encapsulation for electromagnetic interference shielding application. Textile Research Journal. 2023;0(0). doi:10.1177/00405175231168418 **(Q2, IF:2.3)**
4. **Hu S**, Wang D, Venkataraman M, et al. Enhanced electromagnetic shielding of lightweight copper-coated nonwoven laminate with carbon filament reinforcement. Journal of Engineered Fibers and Fabrics. 2023;18. doi:10.1177/15589250231199970 **(Q1, IF:2.9)**
5. **Hu S**, Wang D, Křemenáková D, et al. Mathematical modeling for electromagnetic shielding effectiveness characterization of metalized nonwoven fabrics. Journal of Industrial Textiles, 2023, 53: 15280837231219504. **(Q1 IF:2.2)**
6. **Hu, S**., Wang, D., Večerník, J., Křemenáková, D., & Militký, J. (2024). Electromagnetic Interference (EMI) Shielding and Thermal Management of Sandwich-Structured Carbon Fiber-Reinforced Composite (CFRC) for Electric Vehicle Battery Casings. *Polymers*, *16*(16), 2291. **(Q1, IF:5)**
7. Wang D, **Hu S**, Kremenakova D, et al. The electromagnetic shielding effectiveness of the copper plated nonwoven fabric and its' related comfort properties. Journal of Engineered Fibers and Fabrics, 2022, 17: 15589250221133462. (Q1, IF:2.9)
8. Wang D, **Hu S**, Kremenakova D, Militky J. Evaluation of the wearing comfort properties for winter used electromagnetic interference shielding sandwich materials. Journal of Industrial Textiles. 2023;53. doi:10.1177/15280837231159869 (Q1, IF:3.2)
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10. Wang, D., **Hu, S**., Vecernik, J., Kremenakova, D., Militky, J., & Novotna, J. (2024). Impact of different matrix systems on mechanical, thermal, and electrical properties of carbon fiber reinforced epoxy resin matrix composites. Polymer Composites. (Q1, IF:4.8)
11. Wang D, Venkataraman M, **Hu S**, et al. Multifunctional sandwich materials with ROTIS structure for improved thermal and electrical properties in construction application. Journal of Industrial Textiles. 2024;54. doi:10.1177/15280837241271786
12. Wang, Y., **Hu, S**., Tunáková, V., Niamlang, S., Chvojka, J., Venkataraman, M., ... & Ali, A. (2024). Carbon felt from acrylic dust bags as flexible EMI shielding layer and resistive heater. *Journal of Materials Research and Technology*, *28*, 4417-4427. (Q1, IF:6.2)
13. Tan, X., Jiang, Y., Puchalski, M., Peng, Q., **Hu, S**., Xiong, W., ... & Militky, J. (2024). The multifunctional flexible conductive viscose fabric prepared by thiol modification followed by copper plating. *Cellulose*, *31*(5), 3169-3184. (Q1, IF:4.9)
14. Palanisamy, S.; Tunakova, V.; **Hu, S**.; Yang, T.; Kremenakova, D.; Venkataraman, M.; Petru, M.;

Militky, J. Electromagnetic Interference Shielding of Metal Coated Ultrathin Nonwoven Fabrics and Their Factorial Design. Polymers 2021, 13, 484. https://doi.org/10.3390/polym13040484 (Q1, IF:5)

12.2 Conference papers

15. **Hu S,** Wang D, Yang K, et al. Copper coated textiles for inhibition of virus spread[C]//13th Textile Bioengineering and Informatics Symposium, TBIS 2020. 2020: 84-91.
16. **S. Hu**, et al., : Impact of Morphology and Content of Fly Ash Filler on the Mechanical Properties of Epoxy Resin Composites [C]//Proceedings of the 14th Textile Bioengineering and Informatics Symposium (TBIS 2021), 2021: 326-330.
17. **S. Hu**, et al., : ID127 | Anti-microbial property and ohmic heating effect of copper loaded acrylic fabrics and fiber slivers [C]// Autex 2021 - Unfolding the Future, book of abstracts, (AUTEX 2021), 2021: 199-200.
18. **Shi HU**, Dan WANG, Yordan KYOSEV, Ann-Malin SCHMIDT, Dana KREMENAKOVA. Statistical Fiber-Level Geometrical Model of Thin Non-Woven Structures [C]. TTPF 2021 IASI-RO.(https://doi.org/10.2478/9788366675735-017) (Online publication on 01.2022)
19. **Shi Hu**, Dan Wang, Dana Kremenakova, Jiri Militky, Yuanfeng Wang. Electromagnetic Interference Shielding Simulation of Copper Coated Polyester Non-Woven Fabric And Pore Size Adjusting[C]. Strutex2022.
20. **Hu S**, Wang D, Vecernik J, et al. Sandwich structured carbon fiber composites with enhanced EMI shielding performance[C]//62nd International Conference of Machine Design Departments (ICMD 2022). Atlantis Press, 2024: 305-314.
21. **Shi Hu**, Dan Wang, Mohanapriya Venkataraman, Dana Křemenáková1, Jiří Militký. Parylene-C encapsulated Cu coated nonwovens for thermotherapy application [C]. Autex 2024. Liberec,2024.
22. Wang D, **Hu S**, Venkataraman M, Kremenakova D, Militky J. Influence of ROTIS structure on sandwich material's thermal property for construction application[C], Autex 2024. Liberec,2024.
23. Dan Wang, **Shi Hu**, Dana Kremenakova, Jiri Militky. Factors Influencing the Heat Transfer Performance of the Fabrics [C]. Textile Bioengineering and Informatics Symposium Proceedings (TBIS 2022). (DOI: 10.3993/tbis2022)
24. Dan Wang, **Shi Hu**, Dana Kremenakova, Jiri Militky. EFFECT OF ANTI-WASH TREATMENT ON THE WEARING COMFORT PROPERTIES OF THE EMI SHIELDING MATERIAL [C]. Strutex2022.
25. Dan Wang, **Shi Hu**, Dana Kremenakova, and Jiri Militky. Influence of fabric structure parameters on its heat transfer performance [M]. Selected topics in fibrous materials science. (Volume VI 2022-Book chapter 10) ISBN 978-80-7494-607-3
26. Dan Wang, **Shi Hu**, Yordan Kyosev, Dana Křemanáková, Jiří Militký. ANALYSIS OF THE HEAT TRANSFER PROPERTY WITH THE SANDWICH FABRICS BASED ON ANSYS WORKBENCH AND ALAMBETA [C]. AUTEX 2022 Conference Proceedings, 978-83-66741-75-1. (DOI: 10.34658/9788366741751.90)
27. Wang Y.-F., Venkataraman M., Peng Q.-Y., Yang K., **Hu S**., Militký J. Development of Polydimethylsiloxane (PDMS) /Copper-coated Graphite Elastomer for Strain Sensors (2022) Textile Bioengineering and Informatics Symposium Proceedings 2022 - 15th Textile Bioengineering and Informatics Symposium, TBIS 2022, pp. 8 – 15.

28. Xiao-Dong Tan, Qing-Yan Peng, Kai Yang, Yuan-Feng Wang, Tao Yang, Dan Wang, **Shi Hu**, Xiao-Man Xiong, Jana Saskova, Jakub Wiener, Mohanapriya Venkataraman, Jiri Militky. The Effect of Electrode Materials and Ultrasound on Electrochemical Reduction[C]. TBIS proceedings, 2020.
29. Peng Q, Shi-Li Xiao, Xiao-Dong Tan, Kai Yang, Yuan-Feng Wang, Tao Yang, Dan Wang, **Shi H**u, Xiao-Man Xiong, Mohanapriya Venkataraman, Jiri Militky. Dendrimer-grafted PLGA nanofibrous matrix-mediated gene delivery systems[C]. TBIS proceedings, 2020.
30. Yuanfeng Wang, Jiri Militky, Aravin Prince Periyasamy, Mohanapriya Venkataraman, Vijay Baheti, Kai Yang, **Shi Hu**, Dan Wang, Xiao-Dong Tan, Tao Yang. Disinfection Mechanisms of UV Light and Ozonization[C]. TBIS proceedings, 2020.
31. Yuanfeng Wang, Mohanapriya Venkataraman, Kai Yang, Qingyan Peng, **Shi Hu**, and Jiri Militky. (2022). DEVELOPMENT OF PDMS/COPPER-COATED GRAPHITE ELASTOMER FOR STRAIN SENSORS APPLICATION. In CLOTECH 2022: 14th Joint International Conference Proceedings, ISBN 978-83-66741-64-5
32. Dan Wang, **Shi Hu**, Dana Kremenakova, Jiri Militky. Study on Modification of Carbon Fiber Reinforced Epoxy Resin Matrix Composites: A Review. [C]. Textile Bioengineering and Informatics Symposium Proceedings (TBIS 2023). (DOI: 10.3993/tbis2023)

12.3 Book chapters

33. **Shi Hu**, Dan Wang, Dana Křemanáková, Jiří Militký. Characterization and application of EMI shielding textiles [M]. Selected topics in fibrous materials science. (Volume VI 2022-Book chapter 9). ISBN 978-80-7494-607-3.
34. **Hu S**, Kremenakova D, Militký J, et al. Copper-Coated Textiles for Viruses Dodging[M]//Textiles and Their Use in Microbial Protection. CRC Press, 2021: 235-250.
35. **Hu, S**., Wang, D., Křemenáková, D., Militký, J. (2023). Characterization and Multifunction Application of Metalized Textile Materials. In: Militký, J., Venkataraman, M. (eds) Advanced Multifunctional Materials from Fibrous Structures. Advanced Structured Materials, vol 201. Springer, Singapore. https://doi.org/10.1007/978-981-99-6002-6_7
36. Dan Wang, **Shi Hu**, Dana Kremenakova, and Jiri Militky. Influence of fabric structure parameters on its heat transfer performance [M]. Selected topics in fibrous materials science. (Volume VI 2022-Book chapter 10) ISBN 978-80-7494-607-3
37. Dan Wang, **Shi Hu**, Dana Kremenakova, Jiri Militky and Guocheng Zhu. Effect of Textile Structure on Heat Transfer Performance [M]. Advanced Multifunctional Materials from Fibrous Structures, Book chapter 8, page 163-198. DOI: 10.1007/978-981-99-6002-6_8.

13. Appendix- Full texts of commented articles

A1 Ultrathin Multilayer Textile Structure with Enhanced EMI Shielding and Air-Permeable Properties

A2 Statistical Fiber-Level Geometrical Model of Thin Nonwoven Structures

A3 The novel approach of EMI shielding simulation for metal coated nonwoven textiles with optimized textile module

A4 Mathematical modeling for electromagnetic shielding effectiveness characterization of metalized nonwoven fabrics

A5 Washable and breathable ultrathin copper-coated nonwoven polyethylene terephthalate (PET) fabric with chlorinated poly-para-xylylene (parylene-C) encapsulation for electromagnetic interference shielding application

14. Curriculum vittate

Shi Hu

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Education

Bachelor 09.2008-07.2012	Tiangong University, School of Textile Science and Engineering Textile Engineering Final evaluated score: **85%**
Master 09.2012-07.2015	Hochschule Niederrhein, Faculty of Textile and Clothing Technology Technical Textiles Final evaluated score: **85% (Grade: 2.0)** Master thesis grade: **95% (Grade:1.3)**
PhD 10.2019-now	Technical University of Liberec, Faculty of Textile Engineering Textile Engineering **h-index: 6**

Research Experience

05.2021-now	**Research Assistant** Department of Material Engineering (KMI), Faculty of Textile Engineering, Technical University of Liberec
09.2021-02.2022	**Research Intern** Institut für Textilmaschinen und Textile Hochleistungswerkstofftechnik (ITM), TU Dresden
04.2022-now	Academic User CEITEC - Central European Institute of Technology

Research Project

03.2021-12.2021 **Team Leader**	SGS-2021-6025, Effect of geometry and concentration of fly ash and laponite on impact and dynamic mechanical properties of filled epoxy matrix
05.2021-12.2022	Hybrid Materials for Hierarchical Structures (HyHi) project (Reg. No. CZ.02.1.01/0.0/0.0/16_019/0000843)
03.2022-12.2022 **Team leader**	SGS-2022-6012, Permeable and washable copper loaded nonwoven fabrics processed with Parylene encapsulation technology, **Winning one of the best presentations from SGS project** in 2022
01.2023-now	GACR-project Advanced structures for thermal insulation in extreme conditions (Reg. No. 21-32510M)
03.2023- 01.12.2023	SGS-2023-6375, Impact of different matrix systems on selected properties of carbon filaments reinforced composites

Aditional Skills

Computer skills: **Python**, MATLAB, MS Office, ERP system operation

Particular Equipment Operation: SEM, EDX, FTIR, PECVD, Parylene Encapsulation System

Language: **English** (C1, IELTS6.5), **German** (B1), **Chinese** (Native speaker)

15. Recommendation of the supervisor

Recommendation of the supervisor on Ph.D. thesis of Shi Hu MSc.

Thesis title: **Complex Analysis of EMI Shielding Fabrics**

Doctoral student Shi Hu submitted a dissertation for defense in the form of annotated published scientific articles in high-impact journals. The work is focused on textiles shielding electromagnetic radiation, which nowadays are increasingly used both in the field of clothing and technical textiles. Thin (thickness 0.04 to 0.1 mm) thermally bonded, porous polyester non-woven fabrics with deposition of copper particles (MEFTEX Bochemia s.r.o.) are studied. Unlike other solutions, these textiles do not have a compact metallized layer on the surface, but copper particles are fixed on the surface of the fibers, so that porosity and air permeability are maintained on the one hand and flexibility on the other. At the same time, thanks to the perpendicular laying of 2 layers of polyester multifilaments on top of each other (similar to fabrics) and the point thermal bonding, there is low deformability.
The doctoral student observed the influence of the parameters of these simple and layered textile structures on porosity, air permeability and effectiveness of electromagnetic shielding. Significant increase in the effectiveness of electromagnetic shielding was achieved through layering. Furthermore, the student managed to successfully simulate the effectiveness of the electromagnetic shielding of the mentioned structures using the finite element method in the ANSYS system, where mostly insignificant, but also significant differences between the simulated results and real measurements were found. The main problem was the inhomogeneity in the pore size distribution. The doctoral student successfully proposed a new mathematical model for predicting the effectiveness of electromagnetic shielding based on the transformation of the nonwoven fabric structure into a woven fabric structure with the same porosity, thickness and electrical conductivity.
The general problem of coated textiles is reduced resistance in washing, so the next task was to improve resistance in washing while maintaining the required effectiveness of electromagnetic shielding and air permeability. This was achieved by applying chemical vapor deposition of Parylene-C.
Overall, I evaluate the PhD student's dissertation as comprehensive, dealing with the necessary problems, making it possible to construct optimal textile structures with increased efficiency of electromagnetic shielding for various fields of application in practice.
The language proficiency exhibited in the thesis is commendable and satisfies the standards expected at the doctoral level. His exceptional abilities are evidenced by his publication record in journals with high-impact factors. Throughout his research tenure at TUL, he has promoted his findings through the publication of 14 papers in journals with high-impact factors (13 papers Q1, Q2), 5 book chapters, and 18 articles in conference proceedings. Throughout his academic pursuits, he demonstrated a high level of diligence and competency.
The findings of the dissertation are valuable, innovative, and readily applicable in practical settings. Thus, it is highly recommended that the thesis be presented for the final doctoral defense.

During the plagiarism check, 5% similarities was found with V. Tunáková's habilitation, which used the same measurement method, but this information does not affect the original results of student Shi Hu's dissertation (it is a description of the standard measurement method, citations from the standard, citations of some publications). The same is the case in other similarities of 2.6% and smaller.

Liberec January 20, 2025

Doc Dr. Ing. Dana Křemenáková
Supervisor

16. Opponent's reviews

TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Textile Engineering

Assessment of PhD Thesis

Aspirant:	**Shi Hu, M.Sc.**
Thesis title:	**Complex Analysis of EMI Shielding Fabrics**
Specialization:	**P0723D270003 Textile Engineering**
Supervisor:	**doc. Dr. Ing. Dana Křemenáková**
Reviewer:	**doc. Ing. Antonín Potěšil, CSc.**

Topicality of the thesis

Comment:
The topic of the submitted dissertation is topical and respects current and future innovative trends that are directed towards the use of textile material structures with functional surface treatment oriented to electromagnetic shielding or interference (EMI) in real conditions. The aim is their subsequent use not only in consumer but also in industries with demanding environmental conditions.

excellent[1]	X	above standard		standard		substandard		weak	

[1] Mark selected with a cross

Meet the objectives of the thesis

Comment:
Although structured in the form of summary scientific articles, the submitted dissertation has a very well-developed descriptive part and explains the approaches to the preparation and testing of multi-layered textile material structures with functional treatment with metal particles primarily intended for electromagnetic shielding.
The thesis has good factual content with an indication of the laboratory experimental technologies used to enhance the functionality of the textile material structures. After studying the thesis as a whole, I conclude that the defined aims and objectives of the PhD student have been met.

excellent		above standard	X	standard		substandard		weak	

Methods and solutions

Comment:
A few physical testing methods, procedures and measuring devices were used to characterize the properties of the textile structures used and prepared by the PhD student The thesis also employed the method of numerical simulation of electromagnetic phenomena (FEM) using the High Frequency Module (HFFS) in the ANSYS environment. The thesis shows the independence of the author of the dissertation to the above experimental and numerical methods and activities.

excellent		above standard	X	standard		substandard		weak	

Results of the Thesis - specific benefits of the student									
Comments: The main contribution of the dissertation is the identification and comparison of the properties of textile structures oriented to effective electromagnetic shielding under different conditions of their use, e.g., increased resistance during washing aimed at good air permeability and climatic comfort. The reported experimental findings are treated statistically and provide useful information for practical applications.									
excellent		above standard	X	standard		substandard		weak	

Significance for practice and for the development of the scientific branch									
Comments: The work is a good starting point for further research and development activities in the field of the use of these textile structures in various industrial applications. I recommend that follow-up work should be oriented more deeply into the theoretical areas of physical properties of composite materials with respect to downstream processing technologies in product manufacturing as well as to their specific applications in industrial practice.									
excellent	X	above standard		standard		substandard		weak	

Formal layout of the Thesis and its language level									
Comments: The thesis is logically structured, the English text is comprehensible, the Czech version of the abstract has no editing errors.									
excellent	X	above standard		standard		substandard		weak	

Comments, questions, recommendations

1. The properties of the tested materials are given in the paper for normal room temperatures. For the presumably expected applications of these textile materials in composite structures in other industries (automotive, aerospace, etc.) it is a standard requirement to know the material properties in the temperature range of ca. -60 to 90°C or more. How could this issue be approached?
2. For eventual predictive CAE/FEM simulations, composite structures should be considered as anisotropic or orthotropic material continuum. Using what relations are given in Solid Continuum Mechanics, in such cases, is the relationship between stress and strain, which is the consequence or response to the loading conditions of the respective product of manufacture during its operation, described? Give examples.

Final evaluation of the Thesis

Based on the above review I recommend submitting thesis for defense in front of the scientific committee for the defense of doctoral thesis.

I recommend after a successful defense of the dissertation grant Ph.D.[2]	*yes*	~~*no*~~

[2] Delete where applicable

Place and Date: In Liberec 2.12.2024 *Signature:* Antonín Potěšil

Review to dissertation titled "Complex Analysis of EMI Shielding Fabrics"

Electromagnetic interference (EMI) shielding has attracted more and more attention by researchers as well as ordinary people since the excessive electromagnetic wave could increase the health risks, and damage the equipment. Textiles have been played an important role in protecting people and equipment from EMI. Therefore, the subject of this dissertation is both significant and deserving of in-depth study.

This dissertation aims to develop a mathematical model and simulation method for metalized nonwoven textiles, to improve the washing ability, anti-abrasion property, acid and alkali resistance of metalized nonwoven textiles, and to fill the gap between electromagnetic shielding simulation and shielding effectiveness prediction models for metalized nonwoven textiles.

In the State of the Art section, research on the metallization of textiles, EMI shielding performance of metalized textiles, EMI shielding modeling and simulation, mathematical models for EMI shielding, and washing durability treatments of metalized textiles was introduced, highlighting current challenges and emphasizing the importance of addressing these issues.

In the Metal Particles Coated Nonwovens section, the sample components, preparation procedures, and structural parameters were clearly described. The methodology was appropriate, and the experiments were well-designed and effectively implemented.

In the remainder of the dissertation, the results for analyzing the EMI shielding performance of metalized nonwovens, developing EMI shielding simulations, geometrical modeling of nonwovens, mathematical modeling for predicting EMI shielding effectiveness, and improving the washing durability of metalized nonwovens with good air permeability were presented concisely. The conclusions of this dissertation work are supported by the experimental results. And all of these results were published in SCI journals by the Ph.D. candidate.

Generally speaking, this dissertation was systematically designed and executed. It is logically written and well-structured, with experiments and results presented concisely; making a significant contribution to EMI shielding using metalized nonwoven textiles.

During the Ph.D. study, the candidate as the first author has published 6 papers in SCI journals, 7 international conference papers, and 3 book chapters, which indicates that the candidate has made strong contribution to the field of EMI shielding by focusing on nonwoven fabrics with surface metal coatings. Therefore, I recommend the Ph.D. dissertation for defence.

While the research offers considerable advancements, a few points for clarification and improvement are as follows:

- The discussion on the real-world applications of multilayer structures remains limited. Could the Ph.D. candidate elaborate on potential industry adoption and scalability of these methods?
- The accuracy of the proposed mathematical model is validated against experimental data. How does this model prediction accuracy compare to other existing metalized nonwovens and how about in terms of computational efficiency?
- The washing durability results for coated samples are promising. However, further exploration into the long-term effects of repeated wash cycles on both permeability and shielding effectiveness could strengthen the conclusions. Why the Ph.D. candidate only did 10 times washing cycle? Is there any possibility to increase the washing cycles?

Reviewer: 2024.11.18

Assoc. Prof. Guocheng Zhu

College of Textile Science and Engineering (International institute of silk)

Zhejiang Sci-Tech University