

Article

Carbon Nanotube-Enhanced Silicone Fingerprint Replicas for Biometric Security Testing

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Abstract

Biometric authentication systems, including fingerprint readers, are widely used in mobile devices but remain vulnerable to spoofing attacks. This paper evaluates the properties of carbon nanotube (CNT)-modified silicone fingerprint replicas for use in security testing. Microscopic analyses, roughness measurements, and electrical conductivity measurements showed that the effectiveness of the replicas depends on the type of silicone matrix and the concentration of CNTs. Replicas made with Double 32 at 3% CNT exceeded the percolation threshold, achieving significantly higher conductivity. In practical tests, capacitive scanners proved susceptible to recording artificial prints, while ultrasonic readers were more resistant. The results indicate that although CNTs improve the properties of replicas, their ability to reproduce higher-order features remains limited.

Keywords: dactyloscopic; fingerprints; TouchID; identification; security



Academic Editors: Hariton-Nicolae Costin, Cristian Rotariu and Gladiola Petroiu

Received: 10 October 2025

Revised: 17 October 2025

Accepted: 25 October 2025

Published: 29 October 2025

Citation: Romanczuk-Ruszk, E.; Orłow, A.; Sztorch, B.; Dydek, K.; Przybyszewski, B.; Przekop, R.E. Carbon Nanotube-Enhanced Silicone Fingerprint Replicas for Biometric Security Testing. *Appl. Sci.* **2025**, *15*, 11539. <https://doi.org/10.3390/app152111539>

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1. Introduction

Human identification is based on unique physical, functional, or psychological traits. Among various forensic methods, DNA comparison and fingerprint analysis are the most common because they are safe, simple, and relatively fast [1,2]. Fingerprint examination, or dactyloscopy, is based on three rules: the uniqueness of ridge patterns, the permanence of papillary lines, and the possibility of identification through systematic comparison [3,4]. The structure of fingerprints develops during prenatal development (between the 10th and 17th week of pregnancy) and remains unchanged throughout life, even in identical twins [5].

With rapid technological advances, mobile devices increasingly require secure access to confidential personal data. Traditional methods, such as PIN codes and passwords, are easy to crack [6–8], leading to the widespread use of biometric authentication systems based on fingerprint, facial, or retinal recognition [9–12]. Currently, it is popular to use a fingerprint authentication system to unlock a smartphone. The smartphone is unlocked after the fingerprint is scanned into the sensor [12]. These methods offer greater security and convenience, but the growing use of biometrics has also led to the emergence of

biometric spoofing. This phenomenon involves the creation of artificial fingerprints from materials such as gelatin, latex, or silicone in order to bypass authentication systems [13].

Smartphones use sets of sensors that allow them to receive multiple measurements, so it is possible to unlock the phone with fingerprints or face reflections. The most popular technology adopted by producers is called Micro Electro-Mechanical Systems (MEMS). Smartphones with different systems (iOS, Android) are equipped with different sensors, such as: gyroscope, accelerator, camera, magnetometer [13–15]. Smartphone companies such as Apple, Samsung and Xiaomi use this fingerprint scanning technology to increase data security on mobile devices. The most common fingerprint reading system is a capacitive scanner, which uses electrical conductivity in the human body. Upon contact with a finger, the charge generated in mini-capacitors is discharged, with more discharges recorded on ridges and fewer on valleys [15,16]. Another commonly used system is an ultrasonic scanner, which works like a sonar probe. Sound waves bounce differently off ridges and grooves, creating a detailed 3D map that cannot be fooled by a 2D image [17,18]. The third type of systems are optical scanners, which operate on the principle of light reflection through a prism. In order to generate a fingerprint image, different angles of reflection are recorded [19,20].

However, recent studies indicate that the effectiveness of fingerprint sensors varies: capacitive scanners are particularly vulnerable to silicone forms, while ultrasonic and optical scanners offer greater resistance to 2D attacks, although none of them are completely immune to security breaches. Therefore, analyzing the quality of fingerprint replicas and their ability to deceive readers has become an important aspect of both the development of new mobile authentication solutions and the advancement of forensic research on biometric forgeries [21,22]. From a forensic perspective, such research combines material analysis with practical testing of biometric systems, enabling the assessment of sensors' susceptibility to spoofing and supporting the development of quality standards for research replicas. Microscopic techniques also allow for the evaluation of fine details of fingerprints (minutions, pores, ridge edges), which is crucial for interpreting the results of experiments and their practical significance [22].

In the presented work, the quality of fingerprint castings made of two types of silicone mass with carbon nanotube additives was evaluated. Two addition-cured silicones were selected because of their different Shore A hardness and curing characteristics, which allow evaluating how the mechanical properties of the polymer matrix influence fingerprint replica quality and conductivity. Carbon nanotubes (CNTs) were chosen as the conductive nanofiller due to their high aspect ratio, excellent intrinsic electrical conductivity, and good chemical compatibility with silicone matrices, which together enable the formation of stable conductive networks at relatively low filler contents. Compared with other fillers such as carbon black (CB), graphene oxide (GO), reduced graphene oxide (rGO), or MXene, CNTs provide superior flexibility and dispersion stability without significantly compromising the elasticity and surface fidelity of soft polymer replicas, properties essential for realistic fingerprint reproduction and interaction with capacitive sensors [23]. The addition of carbon nanotubes increases the conductivity of the silicone matrix, enabling more realistic interaction with capacitive sensors. As a result, the proposed replicas more accurately reproduce the morphology of the ridge and the sensor response, providing a more reliable tool for evaluating the robustness of biometric security systems. The replicas were examined by microscopic observation and surface roughness analysis to assess the fidelity of ridge reproduction. Finally, their effectiveness was tested in unlocking trials on four different smartphone models equipped with various types of fingerprint sensors. This combined approach allows for a comprehensive evaluation of both the material quality of the replicas and their practical applicability in biometric security testing.

2. Materials and Methods

2.1. Fingerprint Mold

The fingerprint molds are designed and printed in additive FDM technology. The design was made in SolidWorks (Waltham, MA, USA, <https://www.solidworks.com/>) and the printing parameters are given in Table 1.

Table 1. Three-dimensional printing parameters.

Parameters	
Layer height	0.2 mm
Filling density	10%
Print speed	135 mm/s
Nozzle diameter	0.4 mm
Nozzle temperature	210 °C (483 K)
Table temperature	50 °C (323 K)

2.2. Polymer Impression Material

The study used Zhelmarck Platinum impression material (Salem, MA, USA), commonly used in dentistry. In accordance with the manufacturer's recommendations, the base component was mixed with the catalyst in proportions 1:1. The mass was mixed for about 40 s and finger squeezed for 2 min. After this time the finger was removed and the mass was allowed to fully cross-link (Figure 1).



Figure 1. Examples of impressions made with Zhelmarck Platinum impression material.

2.3. Preparation of Castings

The next step was to make the castings. Two types of commercial silicone were used to make the casts: AD Special (Feguramed GmbH, Buchen, Germany) and Double 32 (Zhermack SpA, Badia Polesine RO, Italy). To increase electrical conductivity, carbon nanotubes were added in concentrations of 2% and 3% in silicone. The properties of the silicones used in the study are presented in Table 2. Figure 2 shows a diagram of the fingerprint casting process.

Table 2. Properties of silicone [24,25].

Properties	AD Special	Double 32
Shore A hardness	18–20	32
Mixing time	~1 min.	~1 min.
Working time	~5–6 min. (22 °C)	~10 min.
Setting time	~30 min. (22 °C)	~20 min.

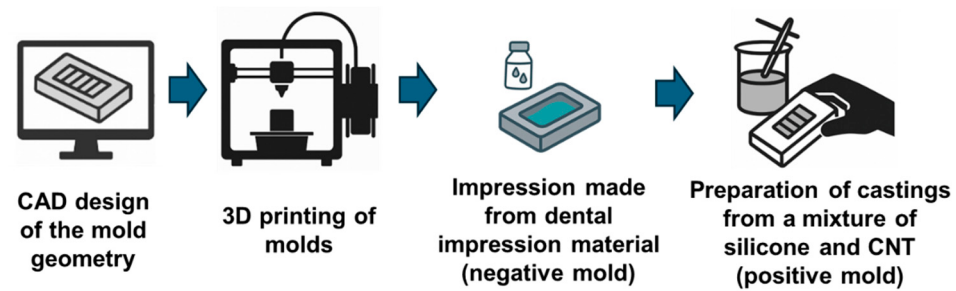


Figure 2. Diagram of the fingerprint casting preparation process.

2.4. Characteristics of the Impression and Castings

A sample of the Zhelmarck Platinum stock was set aside for 6 days and stored in the dark at room temperature. After this time, the hardness was tested by the Shore A method. The test was carried out on a flat surface at room temperature. Five measurement tests were performed. The indenter application points were located approximately 9.5 mm from the specimen edge and equally spaced from each other to avoid mutual influence. The readings were recorded after 1 s and 15 s from pressing the indenter against the sample surface, in accordance with the standard procedure for Shore A hardness testing. The obtained values were then averaged to determine the mean hardness of the tested material.

An optical microscope (Keyence VK-X1000, Keyence, Japan) was used to analyze the surface of the fingerprints. In addition to standard ink prints, replicas made of two different silicone materials with carbon nanotubes were also examined. To ensure greater accuracy and minimize the presence of air bubbles, the silicone casts were degassed in a vacuum chamber before microscopic observation.

The surface morphology of the samples was analyzed using an optical confocal microscope (S neox, Sensofar S.L., Sensofar Metrology, Terrassa, Spain) equipped with a 20× EPI objective lens. The measurements were performed in confocal mode with a lateral resolution of 0.69 $\mu\text{m}/\text{pixel}$ and a vertical scanning range of 89 μm . The scanned area was $850.08 \times 709.32 \mu\text{m}$, with an image size of 1232×1028 pixels. Acquisition was carried out using the SensoSCAN 6 software (version 1.8.0.0) with the Coarse Shift Single algorithm and a threshold of 5%. The total acquisition time for a single measurement was approximately 28 s. All measurements were performed in a non-contact mode under controlled laboratory conditions.

The conductivity of the castings was determined using the two-electrode method, applying metal electrodes to one or both sides of the sample surface. The resistance values obtained were converted into conductivity. In order to ensure repeatability of the results, measurements were performed on five samples. The tests were conducted under standard laboratory conditions.

In addition, fingerprints obtained from various materials were checked on devices using biometrics as a security system, i.e., Mobile phone Xiaomi Redmi Note 10 Pro, Mobile phone Samsung Galaxy A50 (ultrasound machine), Lexar Jumpdrive Fingerprint F35 Pendrive (capacitive scanner), Samsung S20 Ultra phone (ultrasound machine), Fingerprint Bag Lock.

3. Results and Discussion

3.1. Assessment of the Structure and Hardness of Impressions

Figure 3 shows a comparison of two methods of fingerprint imaging—a standard ink impression on a sheet of paper (Figure 3a) and a microscopic image of the impression surface made using Zhelmarck Platinum impression material (Figure 3b). The ink impression served as a reference sample, as it is a commonly used method of fingerprint

documentation in dactyloscopic practice. In both cases, the impression of the same finger was used, and the measurements of the width of the ridges and valleys were taken in the same places. The analysis showed that for the ink impression, the distance between the grooves was $105.90\ \mu\text{m}$, while for the Zhermarck Platinum impression, it was $174.82\ \mu\text{m}$. The lower value obtained for the standard fingerprint was due to the flattening of the ridges of the fingerprints in the case of ink prints, which occurs when the finger is pressed against the paper, causing them to widen and reduce the measured distance. This difference indicates that the ink impression method, despite its simplicity and ease of interpretation, does not fully reflect the actual geometry of the skin ridges.

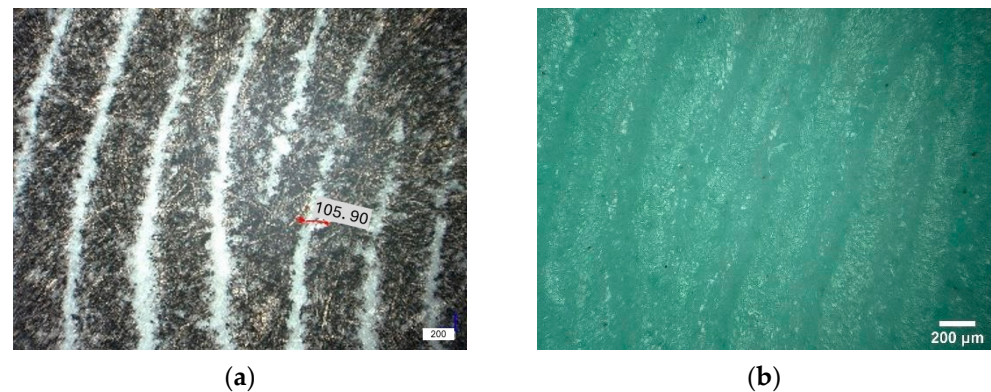


Figure 3. The optical microscope photo of: (a) ink fingerprint, (b) impression material Zhermarck Platinum.

Microscopic observations also showed significant technical problems related to the analysis of the silicone impression. The porous structure of the impression material made it difficult to interpret the image clearly, and the glossiness of its surface caused light reflections that reduced contrast and detail clarity, even when polarization filters were used. An additional challenge was the three-dimensional nature of the cast—protrusions and deep grooves made it difficult to transfer the image to a clear, two-dimensional microscopic view, resulting in insufficient shadow contrast. In comparison, the ink impression, although susceptible to artifacts related to paper texture and flattening of fingerprints, was characterized by greater image clarity and easier metric measurements.

The Shore A hardness test was performed on a flat surface of the samples at room temperature (Table 3). To ensure repeatability of the result, five independent measurements were made, in which the indenter contact points were approximately 9.5 mm away from both the edge of the sample and each other. The readings from the hardness tester were recorded 1 s after pressing the foot and after 15 s. The values obtained averaged 85.8 Shore A (after 1 s) and 84.8 Shore A (after 15 s), indicating a minimal decrease in hardness related to the duration of the pressure force. The results obtained are consistent with the value declared by the manufacturer (85 Shore A), which confirms the stability of the material. The slight difference between the readings after 1 and 15 s suggests that the impression material has good creep resistance and dimensional stability under load.

Table 3. The Shore A hardness.

Measurement No.	Hardness Reading (1 s)	Hardness Reading (After 15 s)
1	85	85
2	87	85
3	85	84
4	87	85

Table 3. Cont.

Measurement No.	Hardness Reading (1 s)	Hardness Reading (After 15 s)
5	85	75
mean and standard deviation	85.8 ± 1.1	84.8 ± 0.4

3.2. Analysis of Castings

Microscopic observations of fingerprint casts made from two types of addition silicones with the addition of carbon nanotubes in various concentrations are shown in Figure 4. In AD Special silicone without nanotubes (Figure 4a), the outlines of the slats are visible, but the surface is characterized by numerous irregularities and local porosity, which may hinder the precise interpretation of second- and third-order details. The addition of 2% nanotubes (Figure 4b) clearly changes the surface morphology: a more heterogeneous structure appears with elongated artifacts running along the direction of the slats. At a higher concentration of 3% carbon nanotubes (Figure 4c), the surface becomes even rougher and the contours of the slats are less distinct, suggesting a deterioration in the quality of the image when the filler content is excessive.

Different results were obtained for Double 32 silicone. The variant without nanotubes (Figure 4d) allowed for smooth castings with a clearly visible slat structure and a relatively low level of background interference. The addition of 2% nanotubes (Figure 4e) caused local surface heterogeneity in the form of scattered clusters, but the outline of the slats remained clear. With a content of 3% nanotubes (Figure 4f), a further increase in roughness and partial blurring of the slat boundaries is visible, similar to the case of AD Special silicone.

Figure 5 shows the surface roughness parameters (S_a , S_q , S_z) of castings made from two types of silicone and their modifications with carbon nanotubes. In the case of AD Special silicone, the S_a and S_q parameters remained at a similar level in all variants, indicating that the addition of nanotubes did not significantly affect the average surface roughness. The S_z parameter showed only slight changes, a decrease at 2% nanotubes, then an increase at 3%, which may indicate the local formation of nanofiller clusters.

Different trends were observed for Double 32 silicone. Both S_a and S_q decreased significantly with increasing nanotube concentration, which clearly indicates surface smoothing and reduction in height irregularities. The S_z parameter also decreased, from $119.13 \mu\text{m}$ for the sample without additives to $84.26 \mu\text{m}$ for the sample with 3% nanotubes. The results confirm that, in the case of this material, the nanofiller effectively improves surface homogeneity.

A comparison of the two silicones shows that their response to the addition of nanotubes is different. AD Special showed little sensitivity to modification, while Double 32 showed a significant decrease in roughness as the percentage of nanotubes increased. These results indicate that the choice of a specific silicone matrix is crucial for the effectiveness of the nanofiller and the quality of the castings obtained.

3D images of the cast surfaces (Figure 6) allowed for a detailed assessment of the topography of the samples and confirmed the quantitative results of the roughness parameters (Figure 5). In the case of AD Special silicone (Figure 6a–c), a relatively high surface irregularity was visible regardless of the addition of nanotubes. The variant without additives (Figure 6a) was characterized by the presence of clear peaks and depressions. The addition of 2% nanotubes (Figure 6b) did not result in significant smoothing, and at a concentration of 3% (Figure 6c), the surface still showed significant height variability, which correlates with slight changes in the S_a and S_q parameters.

Significantly different results were obtained for Double 32 silicone (Figure 6d–f). The sample without additives (Figure 6d) already had a more even structure than AD Special.

The addition of 2% nanotubes (Figure 6e) led to further smoothing of the surface and a reduction in height differences, as confirmed by lower Sa and Sq values. The variant with 3% nanotubes (Figure 6f) showed good overall uniformity, but in some places there were clusters causing local increases in height (higher Sz values).

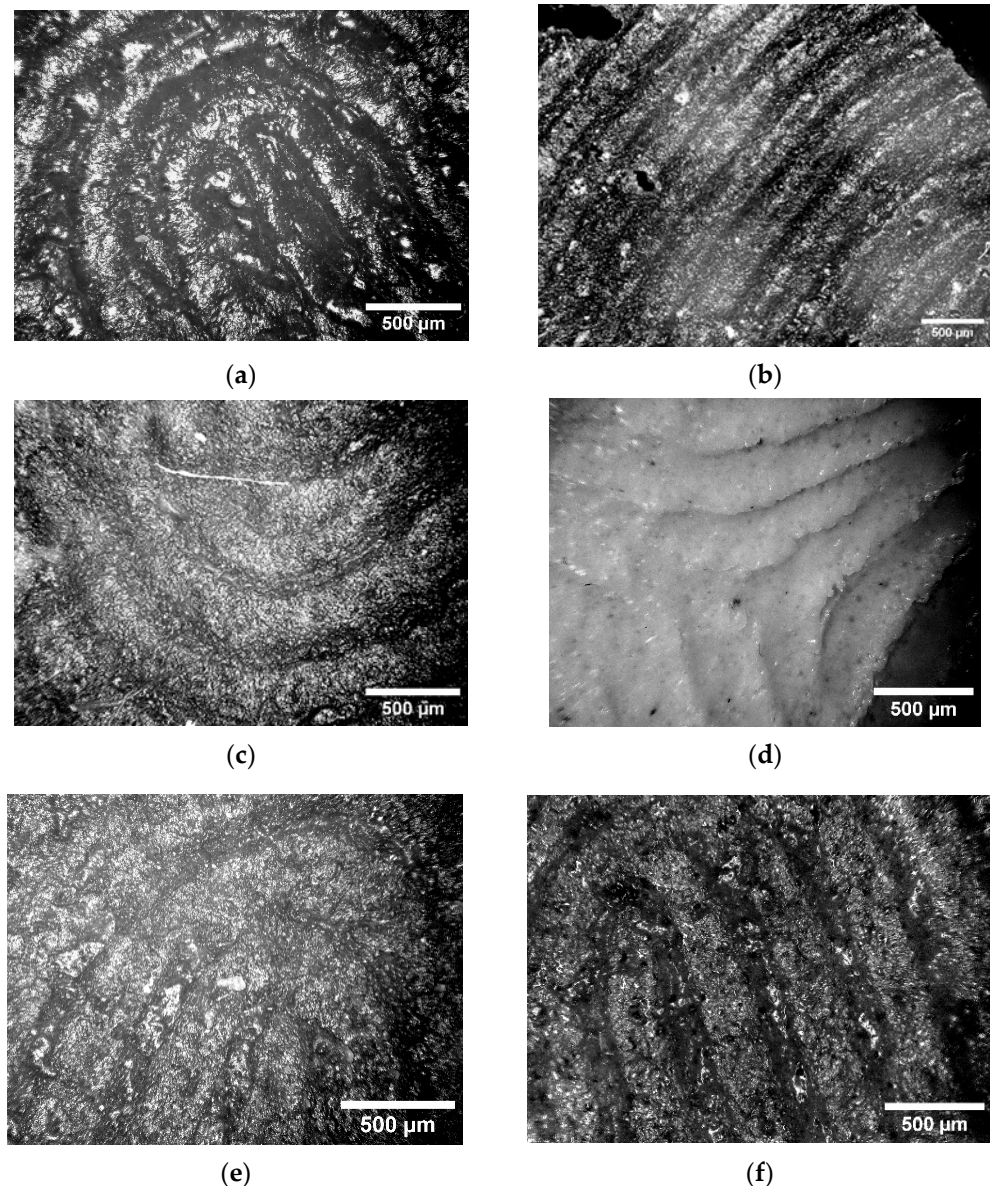


Figure 4. The structure of the castings with the addition of: (a) AD Special silicone without nanotubes, (b) AD Special silicone with 2% carbon nanotubes, (c) AD Special silicone with 3% carbon nanotubes, (d) Double 32 silicone without nanotubes, (e) Double 32 silicone with 2% carbon nanotubes, (f) Double 32 silicone with 3% carbon nanotubes.

As shown in Figures 4 and 6, microscopic images revealed that increasing the CNT concentration caused noticeable changes in the surface topography of the replicas. The surface became more uniform, and in the sample containing 3% CNT, local areas of filler clusters were visible, suggesting the partial formation of a continuous conductive network. Such aggregation zones correspond to better charge transport and a smoother morphology compared to the sample with a lower CNT content. Similar effects have been observed in carbon-filled polymer systems, where the addition of conductive carbon nanoparticles increases surface uniformity and facilitates percolation by forming larger, connected clusters. Muthusamy et al. [26,27] observed that increasing the carbon content in P(VDF-TrFE)

composites with carbon black leads to improved surface continuity and charge transport efficiency, confirming that controlled carbon dispersion is critical for achieving uniform morphology and electrical stability. The consistency of our results with these studies indicates that the formation of CNT clusters in silicone replicas similarly contributes to improved conductivity and a smoother surface.

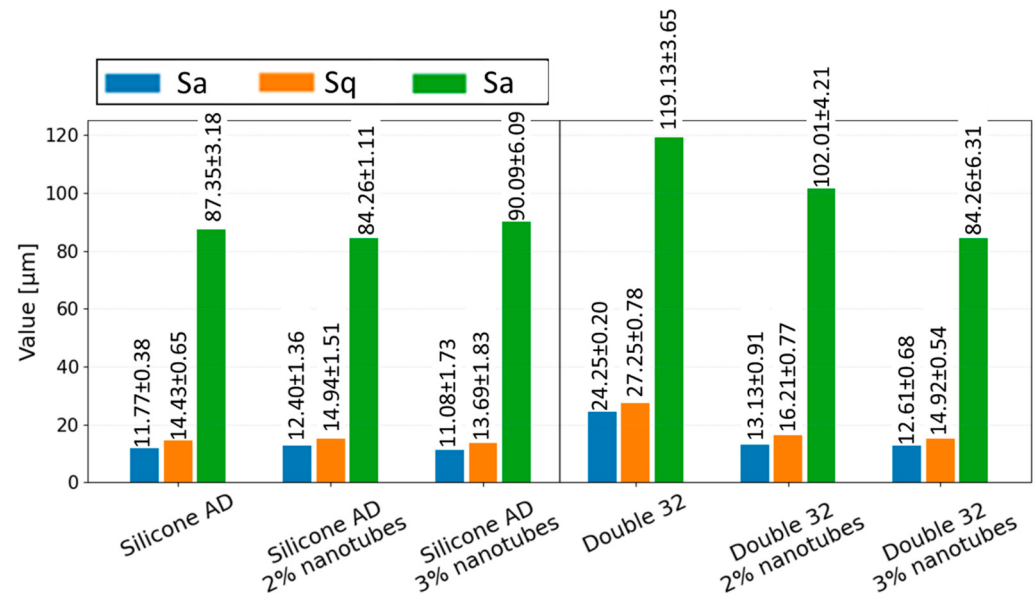


Figure 5. The surface roughness parameters of the castings (Sa—arithmetical mean height, Sz—Maximum height, Sq—Root mean square height) of tested samples.

The results indicate that the effect of nanotubes on the morphology of castings depends on the type of silicone used. In the case of AD Special, the changes were minimal, while Double 32 showed a clear smoothing of the surface with the addition of nanotubes, especially at a concentration of 2%. This suggests that the choice of polymer matrix plays a key role in the effectiveness of nanofiller modification.

The conductivity values of the tested samples are summarized in Table 4. In the case of silicones without additives, very low conductivity values were obtained, typical for dielectric materials, 0.0151 S/m for AD Special and 0.0078 S/m for Double 32 (single-sided measurements), respectively. This means that in their unmodified state, both materials are practically non-conductive.

Table 4. Conductivity of tested samples.

Type of Silicone	Percentage of Additives	Conductivity [S/m]	
		One Side	Two Sides
AD Special	without	0.0151 $\pm$ 0.0011	0.0559 $\pm$ 0.0017
	2%	0.0223 $\pm$ 0.0018	0.0615 $\pm$ 0.0011
	3%	0.0253 $\pm$ 0.0019	0.1736 $\pm$ 0.0069
Double 32	without	0.0078 $\pm$ 0.0006	0.0532 $\pm$ 0.0014
	2%	0.0595 $\pm$ 0.0021	0.1014 $\pm$ 0.0086
	3%	0.1621 $\pm$ 0.0072	0.8443 $\pm$ 0.0199

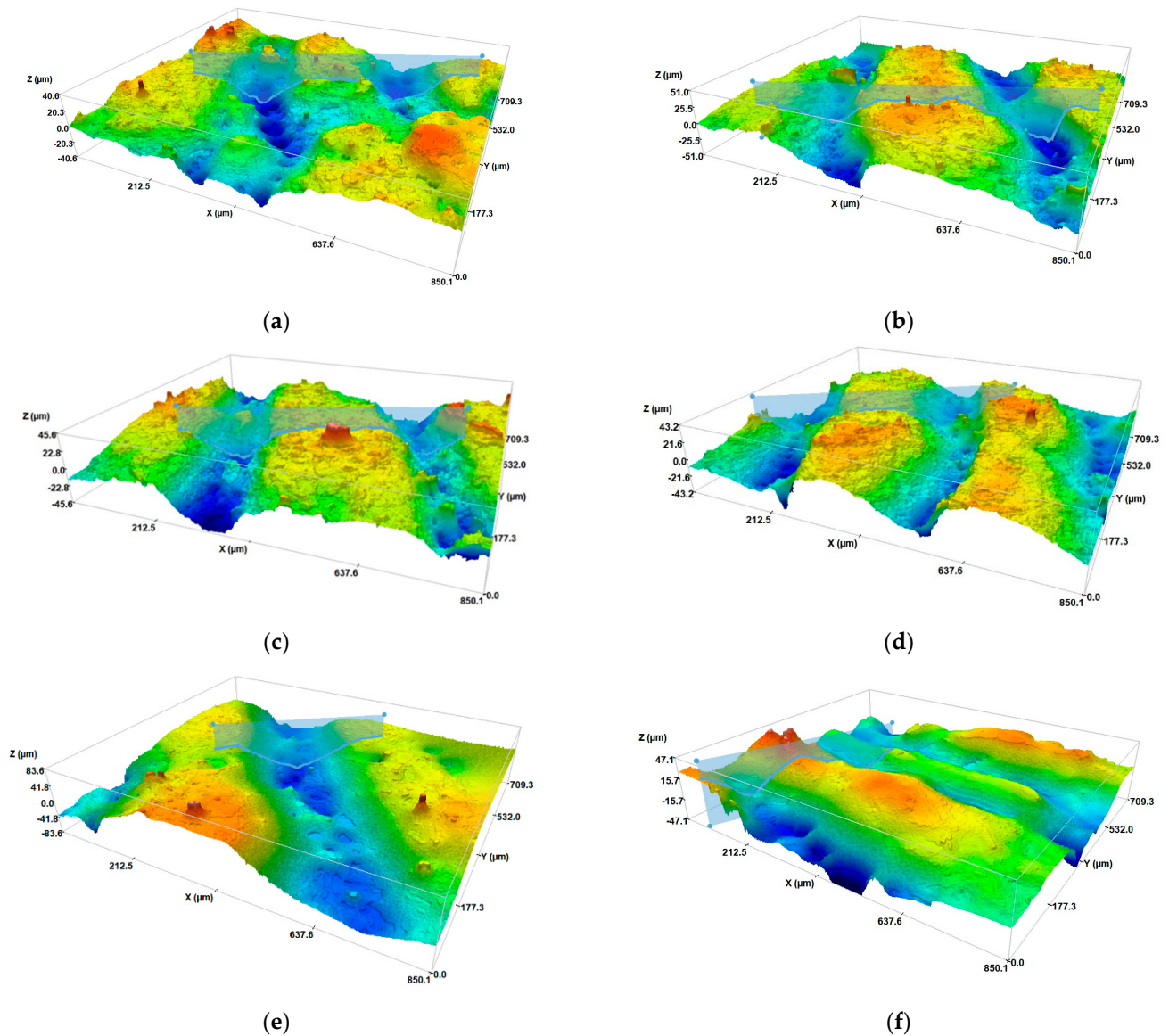


Figure 6. Image of the 3D structure of fingerprint castings made from different silicones: (a) AD without additives, (b) AD with the addition of 2% nanotubes, (c) AD with the addition of 3% nanotubes, (d) 32 without additives, (e) 32 with the addition of 2% nanotubes, (f) 32 with the addition of 3% nanotubes.

The addition of carbon nanotubes caused a marked increase in conductivity. For AD Special, this increase was moderate: conductivity at 2% nanotubes was 0.0223 S/m, and at 3% it increased to 0.0253 S/m (one-sided). A much greater change was observed for Double 32 silicone. Already at 2% nanotubes, the conductivity reached 0.0595 S/m, and at 3% it reached 0.1621 S/m, which indicates better dispersion of the filler and more effective formation of a conductive network.

In addition, the conductivity data obtained in this study also allow the percolation threshold for the tested composites to be determined (Table 4). In the case of Double 32 silicone, a clear, non-linear increase in conductivity was observed when the CNT concentration reached 3%, indicating the formation of a continuous conductive network. This abrupt transition from an insulating to a conductive state confirms that the percolation threshold has been exceeded in this system. In contrast, for AD Special, only a gradual increase in conductivity was observed with increasing CNT content, suggesting that the critical filler concentration necessary to form a connected CNT network was not reached. These

results confirm that percolation behavior strongly depends on the structural properties of the silicone matrix, which influence the dispersion of nanotubes and the formation of conductive paths.

These trends were even more marked in bilateral measurements, where conductivity values increased to 0.1736 S/m for AD Special with 3% nanotubes and up to 0.8443 S/m for Double 32 with 3% nanotubes. This means that in the case of Double 32, the so-called percolation threshold was exceeded, and the nanotubes formed an effective path for current conduction.

These are further results that prove that the type of polymer matrix is crucial for the effectiveness of the nanofiller: Double 32 is characterized by a significantly higher susceptibility to modification and achieves higher conductivity.

The results of the response of phone scanners to artificial fingerprints are presented in Table 5. All tested devices registered a response to touch (signaled as a positive “touch” reading), which means that the sensors detected contact between the cast surface and the sensor. However, there were differences in the ability to register an artificial fingerprint as a biometric pattern.

Table 5. The reaction of different scanners to fingerprints: ‘+’—positive reaction, ‘−’—negative reaction.

Device	Xiaomi Redmi Note 10 Pro	Mobile Phone Samsung Galaxy A50 (Ultrasound Machine)	Samsung S20 Ultra	Lexar Jumpdrive Fingerprint F35 Pendrive (Capacitive Scanner)	Fingerprint Bag Lock
Reader touch reaction	+	+	+	+	+
Registering an artificial fingerprint	+	−	+	+	+
Unlocking a device blocked with an artificial fingerprint	+	−	−	+	−
Unlocking a device locked with an original fingerprint	−	−	−	−	−

The Xiaomi Redmi Note 10 Pro and Samsung Galaxy S20 Ultra smartphones allowed the artificial fingerprint to be successfully saved in the system and could then be unlocked using it (Table 5). In the case of the Samsung Galaxy A50, equipped with an ultrasonic reader, it was not possible to register an artificial fingerprint. This confirms the higher resistance of ultrasonic technology to spoofing attempts compared to classic capacitive sensors.

Peripheral devices based on capacitive sensors, such as the Lexar Jumpdrive Fingerprint F35 memory stick or the Fingerprint Bag Lock, also responded positively and allowed the artificial fingerprint to be saved. These results indicate that capacitive scanners may still be vulnerable to fake prints made from silicone materials, while ultrasonic fingerprint recognition systems show greater resistance.

In summary, research confirms that the effectiveness of spoofing attacks largely depends on the technology used in a given device. Capacitive sensors were most susceptible to recording fake fingerprints, while the ultrasonic reader (Samsung Galaxy A50) proved resistant to such attempts.

Capacitive sensors register local changes in the distribution of electrical charge between the sensor electrodes and the contact surface, which is why their response strongly depends on the electrical conductivity and dielectric constant of the replica material. Silicone composites containing carbon nanotubes (CNTs) are characterized by increased conductivity and better dielectric coupling due to the formation of percolation networks that

facilitate charge transport and make their behavior similar to the electrostatic properties of human skin [28]. In contrast, ultrasonic sensors operate on the basis of the propagation and reflection of acoustic waves in the medium being examined, therefore acoustic impedance, density, and elasticity of the material play a crucial role. Impedance mismatch between the silicone replica and biological tissue limits the transmission of ultrasonic waves, which explains the low effectiveness of attacks in this type of sensor [29]. Similar relationships have been shown in modern flexible capacitive and electrostatic sensors, where sensitivity and resistance to spoofing depend on the dielectric properties and mechanical compatibility of the material with the skin surface [30,31].

The results obtained confirm that the effectiveness of materials used to forge fingerprints depends on their mechanical and electrical properties. Rattani et al. [32] pointed out that different materials, such as silicone, latex, and gelatin, reproduce the structure of ridges and valleys in different ways, which affects image quality and the ability to detect them. The research presented in this paper showed a similar relationship: some compositions allowed for accurate reproduction of second-order features, while others generated greater distortions, limiting the effectiveness of the attack. The literature contains information on the use of new materials that better reproduce fingerprints. The work of Saguy et al. [33] showed that modern PEG-based hydrogels can more effectively deceive systems equipped with Presentation Attack Detection (PAD) mechanisms, surpassing standard polymers such as silicone and latex in terms of conductivity and hardness. Comparing the data presented in Saguy's et al. article [33] with the results of this study, it can be seen that the current limitations of replicas can be gradually overcome with the development of more advanced materials that not only reproduce the topography of fingerprints, but also conduct electricity in a manner similar to human skin.

It is worth noting the different systems that are used in devices. Marasco and Ross [34] noted in their work that the effectiveness of anti-spoofing methods is strongly dependent on the type of sensor used: optical sensors are more susceptible to silicone, while capacitive sensors are more easily fooled by gelatin. A similar trend can be observed in this study. Phones with different operating systems responded differently to unlocking attempts. This indicates the need to test security measures in diverse conditions and using multiple classes of materials, as suggested by LivDet standards.

Li [35] demonstrated that carbon nanotubes (CNT)/PDMS systems exhibit a distinct percolation threshold at approximately 0.18 wt.% CNT, above which the electrical conductivity increases by several orders of magnitude, reaching 43.65 S/m at 5 wt.% CNT. A similar phenomenon was reported by Neffati et al. [36] for silicone-carbon black composites, where the percolation threshold was estimated at 0.15 vol.%, confirming that only a small amount of conductive filler is required to form a spanning network and drastically alter the transport properties. More recent studies have emphasized the role of functionalization and processing conditions in enhancing the conductive pathways. Naeem et al. [37] showed that acid-treated and hot-pressed multi-walled carbon nanotubes (MWCNT) films could achieve conductivities as high as 283 S/m at 423 K, attributed to reduced porosity and improved tube-to-tube contacts that facilitate carrier mobility. This is consistent with the wider perspective presented by Maheswaran et al. [38], who found that CNT-polymer nanocomposites can exhibit exceptionally low permeation thresholds, in some cases below 0.01% by volume, due to the high aspect ratio and internal conductivity of CNTs.

The increase in spoofing efficiency for CNT-modified silicones observed in this study is consistent with the results of Sałaciński et al. [28], who demonstrated that homogeneous dispersion of nanotubes improves charge transport and the stability of electrical properties under deformation. Furthermore, the higher effectiveness of deception observed in the study (Tables 4 and 5) above a certain CNT concentration confirms the percolation con-

ductivity model described for similar systems [39]. These results are also consistent with reports on flexible capacitive sensors used in biomonitoring, where adequate filler dispersion and mechanical compatibility with the substrate determine signal stability during repeated deformations [40]. The totality of observations confirms that capacitive sensors remain vulnerable to spoofing when the conductivity and elasticity of the replica material approach the parameters of human skin, while ultrasonic sensors show significantly greater resistance thanks to their acoustic detection mechanism.

The most important point is not so much to maximize conductivity as to achieve it above the minimum threshold necessary to activate the capacitive sensors used in the devices. Therefore, it is not only the concentration of carbon nanotubes that is important, but also the method of their dispersion, functionalization, and material formation process, which together determine the effectiveness of conduction in practical applications.

4. Conclusions

The research carried out in this study showed that silicone fingerprints modified with carbon nanotubes can significantly replicate the physical and electrical properties of real fingerprints. Microscopic analysis and surface roughness measurements confirmed that the effectiveness of the replicas largely depends on the type of silicone matrix used. Double 32, in particular, showed a marked decrease in roughness and a significant increase in conductivity after the introduction of carbon nanotubes, indicating that the choice of base material is crucial for the quality of the castings obtained.

Electrical conductivity tests showed that adding 2–3% carbon nanotubes significantly increases charge transport, and in the case of Double 32, with 3% carbon nanotubes, the percolation threshold was exceeded, enabling the formation of an effective conductive network. Biometric tests showed that capacitive scanners were most susceptible to artificial fingerprint registration, while ultrasonic readers showed greater resistance to spoofing attempts. It is important to note that none of the tested devices were unlocked using replicas when a real fingerprint had been previously encoded, indicating the limitations of silicone casts in the context of newer security systems.

In summary, the results confirm that carbon nanotube-modified silicones can be recognized by some biometric systems, but the quality of detail reproduction and electrical properties remain a limiting factor in the effectiveness of replicas. Further work will focus on optimizing CNT dispersion and curing conditions to ensure repeatable replica quality and conductivity on a larger scale.

Author Contributions: Conceptualization, R.E.P. and B.S.; methodology, R.E.P.; software, E.R.-R., A.O. and B.S.; validation, R.E.P. and E.R.-R.; formal analysis, E.R.-R.; investigation, E.R.-R., A.O., B.S., K.D. and B.P.; resources, R.E.P. and B.S.; data curation, E.R.-R.; writing—original draft preparation, E.R.-R.; writing—review and editing, R.E.P. and B.S.; visualization, E.R.-R.; supervision, R.E.P.; project administration, E.R.-R. and R.E.P.; funding acquisition, R.E.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work was carried out on infrastructure financed by the Intelligent Development Operational Program, project no. POIR.04.02.00-00-D003/20-00; European Funds, project no. RPWP.01.01.00-30-0004/18; and the Ministry of Science and Higher Education, project no. 21/529535/SPUB/SP/2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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