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Analyse of Strain and Stress on Different Stretchable Conductive Ink Materials by Numerical Method

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ABSTRACT

This study determines the optimal stretchability performance of different materials on a conductive pattern by using maximum principal elastic strain and Von Mises stress analysis. It was performed by using finite element analysis (FEA) modelling approaches. The FEA modelling was initiated from previous studies of comparative difference in strain and stress caused by stretching the screen printed straight-line pattern (baseline) and curving wave pattern using graphene conductive ink as material. The research is using a sine wave pattern because it has the best results from the previous studies compared to other patterns. Five different FEA modelling conductive materials were developed, which are copper as the baseline, graphene, carbon nanotube (CNT), carbon black, and silver. The maximum principal elastic strain and equal stress (Von Mises stress) obtained by FEA modelling can be used to approximate which material has better elasticity. After 20% elongation, the maximum principal elastic strain of carbon-based conductive ink carbon black and graphene, 14.521 x 10^{-3} and 14.578 x 10^{-3}, respectively, produced the best results, with percentage difference values of 2.63% and 2.24% from copper (baseline). As compared to the copper (1761.7 MPa) conductive ink, the Von Mises stress value for carbon black (241.76 MPa) and graphene (257.34 MPa) is about 7 and 6 times lower stress respectively. There are no significant differences in strain and stress values between graphene and carbon black conductive inks. The findings show that carbon black can be an alternative to graphene as a good conductive ink. Furthermore, this research demonstrates that the FEA method can be used to investigate the stretchability of conductive ink.

Keywords: Graphene, conductive ink materials, finite element analysis, maximum principal elastic strain, von mises stress

1. INTRODUCTION

Fabric, health, automotive, electronics, and other industries have used stretchable and flexible electronic technologies extensively. Because of its flexibility, a circuit may be mounted on an irregular surface or changed regularly. Since the stretchable base is constantly subjected to cyclic motion and deformation, it provides a benefit for ubiquitous and unobtrusive sensing and display applications [1]. The automotive industry has developed a new technology of flexible and stretchable electronics to provide variety in a consumer vehicle. By introducing metallic flexible interconnection, for example, conventional rigid electronics circuit technology has been improved to a flexible and stretchable circuit. This will give an advantage to capable electronic circuits in terms of bent, stretched and twisted.

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Printed electronics is one of the fastest-growing technologies today, with applications in healthcare, aerospace, advertising, and public transportation. Printed electronics was initially envisioned as a low-cost alternative to silicon-based electronics, its complementary technology [2]. Printed electronics, according to [3], is vital in enabling widespread versatile electronics and, more recently, stretchable electronics. As the market for portable devices and thinner electronics grows, printed electronics are being used to create lightweight keyboards, antennas, electronic skin patches, and more. Conductive ink is an essential component of flexible electronics. It's a type of ink that produces a patterned object that can conduct electricity. Metal nanoparticles, conducting polymers, metal complexes, and inorganic carbon, which plays a major role in conductivity, are examples of conductive ink materials. To formulate conductive inks that can be patterned using inkjet, screen, flexographic, direct writing, or gravure, the conductive ink must have good electrical and mechanical properties [4]. The stretchability and flexibility of five conductive materials, copper, graphene, CNT, carbon black, and silver, will be investigated using FEA strain and stress analysis in this experiment.

Stretchability is important in stretchable electronics industries because it is an evolving class of device that can be squeezed, twisted, and adhered to a very complex form, and the mechanical and electrical compliances of stretchable electronics can pave the way for health care, entertainment, and energy [5]. Stretchable electrodes and interconnects are usually made by combining conductive materials with elastic substrates [6] [7]. Flexible substrates have high electrical insulating properties, stability, clarity, hardness, smoothness, and must be extremely durable and usable in wet and corrosive environments [8].

A sine wave screen printed pattern on a stretchable substrate using stretchable conductive ink is more stretchable than a straight line pattern of similar fabrication [9]. Stretchability is defined as the percentage change in resistance of a printed conductor when exposed to induced uni-axial stress in the context of printed conductors. The stretchability benefits from a lower change in resistance [10]. Wavy patterns are a simple mechanical technique for improving the stretchability of stretchable electronics. Previous research, [11] has shown that sine wave patterns have higher elasticity values than other patterns when compared to straight line (baseline) patterns. The theory is that the wavy or meandering patterns will behave like a spring coil when stretched, opening up and exhibiting greater stretchability [9]. It can be stretched in the same way as a straight-line pattern, but the increase in resistivity is smaller.

The study aimed to show how different conductive materials, such as copper, graphene, CNT, carbon black, and silver, as the copper becomes the baseline induced different strain and stress when stretching a screen printed sine wave pattern. The FEA research mainly focuses on determining the elastic properties of the conductive inks. The maximum principal elastic strain can be determined using experimental findings as an input parameter for material properties in FEA modelling. By evaluating the fatigue in sine wave pattern lines, the difference in pressure and tension during stretching may be optimized. The maximum principal elastic strain and equal stress (Von Mises stress) obtained by FEA modelling can be used to approximate which material has better elasticity. The stress distribution in the conductive ink patterns was evaluated using Von Mises stresses since a higher Von Mises stress indicates a greater probability of failure [12]. Following the achievement of the above-mentioned goal, an attempt was made to determine the best-printed conductor pattern with the best stretchability using maximum principal elastic strain and Von Mises stress obtained from FEA modelling.

1.1 Previous Studies on Pattern Analysis

Previous research [11] has mainly focused on the effects of six different printed patterns, including straight-line (baseline), sine wave, semi-circle, serpentine, zigzag, and horseshoe, on the printed pattern's resulting stresses using graphene as filler loading conductive ink. This study aimed to determine which form would have the least amount of stress based on its percentage value. Table 1 shows the substrate properties derived from previous experimental results as well as the ink supplier. The numerical results were then compared to the experimental outcomes. The FEA of the Knuckle joint was performed using numerical workbench tools. The Knuckle Joint was initially designed in CATIA modelling software, and then stored as an IGES file and inserted into the workbench software. The model then meshed with a fine mesh option, and the computational process would take a reasonable amount of time. ANSYS software was used to simulate strain and stress behaviour of the circuit under mechanical loading using FEA of ink stresses on a wavy pattern and a straight-line screen-printed pattern. The material properties used from previous FEA research are presented in Table 1.

Table 1 Graphene Properties Used for Simulation Analysis [11]

Materials	**Properties**				
	Young's Modulus (Pa)	**Poisson's Ratio**	**Density (kg/m^3)**	**Thermal Conductivity (W/m °K)**	**Resistivity (Ω.m)**
Graphene	15.49×10^9	0.149	2200	5300	0.249

The previous studies of FEA results show that the sine wave pattern is more stretchable than a straight-line pattern. The sine wave pattern, unlike the straight line, acts like a coil and opens up when stretched. According to the FEA results, the straight-line pattern's stretchability after 20% strain exposure is 37 times worse than the sine wave pattern. Previous researchers have conducted FEA experiments on various conductive ink materials by using several different types of patterns to obtain appropriate strain and stress values for flexibility. Table 2 shows previous studies of FEA analysis on strain and stress carried out by researchers using various conductive ink materials and patterns.

Another researchers were investigated the deformation behaviour and failure mechanisms of parallel-aligned, horseshoe-patterned, stretchable conductors encapsulated in a polymer substrate by using numerical and experimental analyses [13]. From the experimental results, the researchers demonstrate that the copper stretchable conductors enable elongation up to 123% and 135% without metal rupture for the fine and coarse pitches, respectively. Using a mechanical model with a line to line pitch of 3.0 mm and a 20% elongation, the researchers discovered that the strain is 35.00×10^{-3}. [14] propose a computational method for predicting effective orthotropic elastic characteristics of carbon nanotubes (CNT) nanocomposites under a variety of constituent conditions. To predict the effective material properties of nanocomposites, the researchers used the Mori-Tanaka (MT) homogenization methodology, which was combined with a finite element method (FEM) approach. The strain and stress values obtained from the FEA using the hollow cylinder model are 13.5 and 1000 MPa, respectively. The researchers also discovered that the interface between the matrix and the filler has a big impact on the effective elastic strength of polymer composites.

The researchers investigated how varied quantities of carbon black particles affected the mechanical performance of carbon fibre-reinforced epoxy composites [15]. Researchers are testing the produced composite materials with tensile, flexural, and impact tests in the early stages of their research. The numerical method was used to validate the experimental finding. The researchers discovered that carbon black/epoxy composites reinforced with carbon fibre exceed conventional carbon fiber-reinforced epoxy matrix composites in terms of mechanical performance. The FEA results from the analytical tensile test is 110.43 MPa which increases by 65.78% as compared to the tensile strength of conventional carbon fabric-reinforced epoxy composite. The electrical and mechanical characteristics of an inkjet-printed patch antenna under uniaxial and biaxial bending were investigated by [16]. Inkjet printing on a polyethylene terephthalate (PET) substrate was used to design and fabricate a 30 mm x 40 mm patch antenna with a truncated copper ground plane. The strain distribution during both uniaxial and biaxial bending was determined using FEA. The researchers observed the maximum strain of 0.0169 under uniaxial bending and 0.0029 under biaxial bending as a result of FEA studies. Strain and stress results were carried by other researchers using various conductive ink materials and patterns as shown in Table 2.

Table 2 Strain and Stress Results Carried by Researchers Using Various Conductive Ink Materials and Patterns

Materials	**Simulation Pattern**	**Maximum Principal Elastic Strain**	**Von Misses Stress (MPa)**	**Reference**
Copper	Horseshoe	35.00×10^{-3}	N/A	[13]
Graphene	Sine wave	14.578×10^{-3}	257.34	[11]
CNT	Hollow cylinder	13.50×10^{-3}	1000	[14]
Carbon Black	Straight line	N/A	110.43	[15]
Silver	Straight line	16.90×10^{-3}	N/A	[16]

1.2 Conductive Materials

Printed circuit boards (PCBs) are physically fragile and easily broken when exposed to high pressure. Low manufacturing costs, long-term durability, environmentally friendly production methods, recycling, lower energy usage and higher performance, and electronic integration as part of other structures are all important new electronic features [17]. To address these issues, various conductive fillers used in the printed electronics industry, such as gold, titanium, carbon nanotubes, silver nanoparticles, organic conductive polymers, and graphene, can be used to replace PCB technology thus lowering production costs. PCB manufacturing infrastructure is diverse with both additive and subtractive conductor production [18]. Metal is one of the high-conductivity materials that has been widely used in conductive parts [19].

Silver is expensive and needs high sintering temperatures to provide high conductivity, which limits its application to flexible substrates [20]. Copper, iron, and nickel are less expensive options due to the high cost of materials, but they have the disadvantage of being readily oxidised in the air, forming an insulating barrier on their surface [21]. Carbon, in the forms of graphite, carbon black, and CNT, is another conductive substance [22] . Carbon black has the advantages of mechanical properties, low specific weight and ease of processing, etc. CNT has the advantage of being able to behave as either a metal or a semiconductor depending on its chirality, and it can survive extreme temperatures [23].

Graphene as a filler has the potential to improve the efficiency, reliability, and durability of many applications for the next generation of electronic devices, composite materials, and energy storage devices due to its excellent electrical, mechanical, and thermal properties [24]. Because of its many attractive properties such as special structure effects, high specific surface area, and high conductivity, graphene has the greatest potential as a high-performance absorption material [25]. With many attractive properties such as high electrical conductivity, mechanical efficiency, and elasticity, graphene has become a major source of research [26]. Graphene strain sensors can detect a variety of strains caused by stretching, bending, and torsion, both of which are essential for sensors to detect human body movements [27].

1.3 Mechanical Properties

The main objective of mechanical characteristics analysis is to determine the material's strength. The hardness of the samples was tested using a nano-indentation machine. The basic concept of nanoindenter testing is to use a high-resolution actuator to drive an indenter into the test surface and a high-resolution to continuously measure the penetration that occurs [28]. Based on the previous experiment, an indentation load of 150mN is used for maximum load because of Young's modulus and maximum depth suitable for this experiment. An indentation load of 150mN is used as the maximum load because of Young's modulus and the maximum depth suitable for this experiment [11].

The maximum load was measured as a function of the indenter's penetration depth into the surface [29]. The depth of the nano-indentation was carefully adjusted to prevent the formulation from cracking and rupturing, and therefore losing its protective effect. The indenter may penetrate too deep if the load is too high, however, this is a major concern when measuring thin films because the results will be affected by the substrate's properties. If the load is too low, the results would be influenced by the roughness of the specimen surface. The nanoindenter test was used to define the printed ink's elastic behaviour. The Young's Modulus can determine the physical properties of the formulation by allowing the bending or stretching of conductive ink circuits. The Young's modulus values from this experiment then were used as the input parameter in the FEA of graphene formulation.

2. METHODOLOGY

The study was conducted through previous experiments data and simulations of FEA. Previous experimental research on graphene material properties was used, as well as simulated maximum elastic strain and von mises stress results. The stress analysis simulations were done using the ANSYS Workbench finite element software.

2.1 Model Configuration

The FEA model was developed with 0.1 mm ink thickness for all patterns. Because of symmetrical geometry along the X direction, a half model was deployed. [9] has used 20% of stretch to determine lifetime under a particular strain of the stretchable conductors. For this research, 20% of elongation stress was deployed uni-axially along the X-axis as shown in Figure 1.

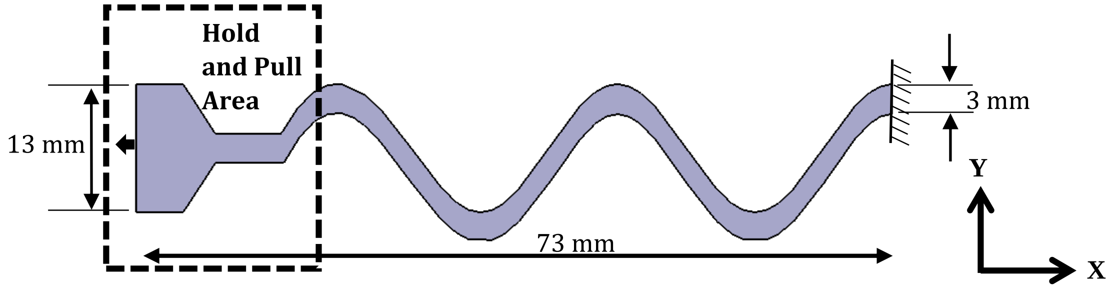

Figure 1. FEA sine wave model [11].

2.2 FEA on Different Conductive Materials

From a mesh, a mesh of nodes has been developed, and the results are determined by numerically solving the governing equations at each node using the finite element method. The sine wave model preference was used with fine mesh option and a reasonable time was required for the computational process as shown in Figure 2. The finite element was generated using the element size of 1.9 x 10^{-4} mm which makes it 8052 elements.

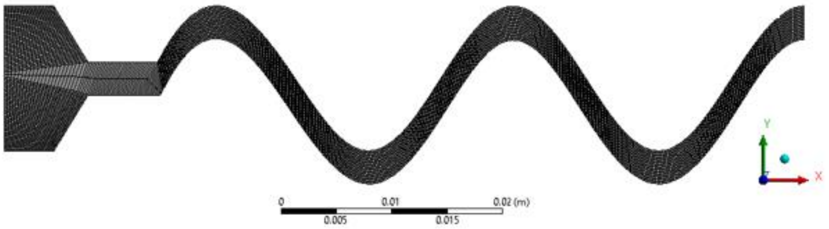

Figure 2. Mesh model of the sample [11].

The material properties used for this FEA research are presented in Table 3. The values differ from the material properties used in this paper, as obtained from previous and other research studies.

Table 3 Material Properties Used for Simulation Analysis

Materials	Properties		References
	Young's Modulus (MPa)	Shear Modulus (Pa)	
Copper	110 x 10^3	4.104 x 10^{10}	[16]
Graphene	15.49 x 10^3	6.741 x 10^9	[11]
CNT	30.612 x 10^3	1.177 x 10^{10}	[14]
Carbon Black	14.11 x 10^3	7.055 x 10^9	[15]
Silver	95.506 x 10^3	3.486+ x 10^{10}	[30]

3. RESULTS AND DISCUSSION

3.1 Comparison between Copper (baseline) and Other Conductive Inks

Table 4 shows the percentage difference between copper (baseline) and other conductive ink on the maximum principal elastic strain and Von Mises stress. The strain can be approximately computed by $\mathcal{E}= \Delta L/L$, where ε is the strain, ΔL is the total elongation from the neutral axis of the pattern structure and L is the original length of the pattern. The hand calculated strain is 17.088 x 10^{-3} for the copper conductive ink. Table 4 shows the maximum principal elastic strain contours of the copper conductive ink derived from numerical simulations, which are compared to the hand-calculated values for expedience. This magnitude 14.908 x 10^{-3} maximum principal elastic strain for copper as shown in Table 3 is close to the hand calculated value of 17.088 x 10^{-3}.

The comparison of the percentage to the copper (baseline) shows that the carbon black is the lowest and is followed by graphene, CNT, and silver. The percentage difference value of carbon black to copper (baseline) is -2.63% for maximum principal elastic strain and -151.73% for Von Mises stress. It can also be stated that the carbon black percentage value is 2.63% lower at maximum principal elastic strain and 151.73% lower at Von Mises stress than a copper (baseline). This can be seen through the observation in Figures 3 and 4 which the maximum value of the strain and stress position is different from other materials. The maximum strain and stress occur at the sharp edge nearest to the force applied to the pattern. The stress developed at this hogging condition is so severe that there is the possibility of a catastrophic break of the pattern at the sharp edge area [31]. All percentage differences are solved using the following equation:

$$\% \, Difference = \frac{(\mathrm{V1}-\mathrm{V2})}{\left[\frac{(\mathrm{V1}+\mathrm{V2})}{2}\right]} \tag{1}$$

where:
V1 = Other conductive ink (maximum principal elastic strain or Von Mises stress) value
V2 = Copper conductive ink (maximum principal elastic strain or Von Mises stress) value

Table 4 shows that copper as a metal-based produces a result that is slightly higher than the result of other materials with 14.908 x 10^{-3} for maximum principal elastic strain or more than 2.63% than the lowest result, carbon black. The FEA results in Table 4 also shows that carbon-based materials like carbon black, graphene and CNT, 14.521 x 10^{-3}, 14.578 x 10^{-3} and 14.853 x 10^{-3} for maximum principal elastic strain value respectively do not have significant differences which can also provide good elasticity than metal-based. For the Von Mises result, copper also showed the highest value compared to all the materials tested. A value of 1761.7 x 10^{3} indicates that copper has a high level of hardness when subjected to pressure and does not possess high stretchability behaviour.

Table 4 FEA Results Summary

Type	Conductive Ink	Maximum Principal Elastic Strain	% Difference to Baseline (%)	Von Misses Stress (MPa)	% Difference to Baseline (%)
a	Copper (Baseline)	14.908 x 10^{-3}	0	1761.70	0
b	Graphene	14.578 x 10^{-3}	-2.24	257.34	-149.02
c	CNT	14.853 x 10^{-3}	-0.37	494.20	-112.37
d	Carbon Black	14.521 x 10^{-3}	-2.63	241.76	-151.73
e	Silver	14.938 x 10^{-3}	+0.20	1519.40	-14.77

Figures 3 and 4 show the comparisons of the maximum principal elastic strain and Von Misses stress for five conductive ink materials. It can be seen that the maximum principal elastic strain and equivalent stress (Von Mises stress) behaviours are different for all conductive ink. Based on the result, the maximum principal elastic strain and equivalent stress are lower on a less Young's modulus of elasticity and shear modulus. The type (d) conductive ink in Figures 3 and 4 attain the smallest amount of maximum principal elastic strain and Von Mises stress among all the five types because the carbon black is carbon-based material which depicts the more spring coil behaviour than other materials. As compared to other carbonaceous materials, carbon black has a higher percolation threshold value, higher sensitivity, and a more consistent strain-dependent response during the durability test performed by [32]. This also shows that carbon black is more suitable to be used as a nanofiller because it possesses a low aspect ratio compared to graphene and CNT [33].

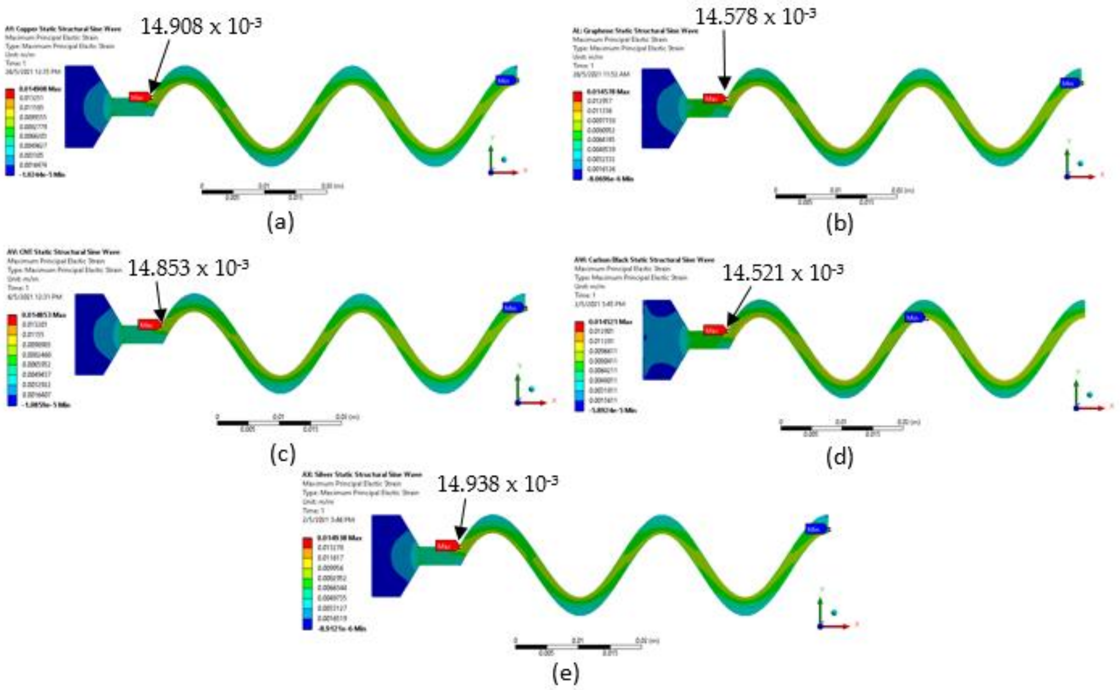

Figure 3. Maximum principal elastic strain of conductive materials. (a) Copper; (b) Graphene; (c) CNT; (d) Carbon black; (e) Silver.

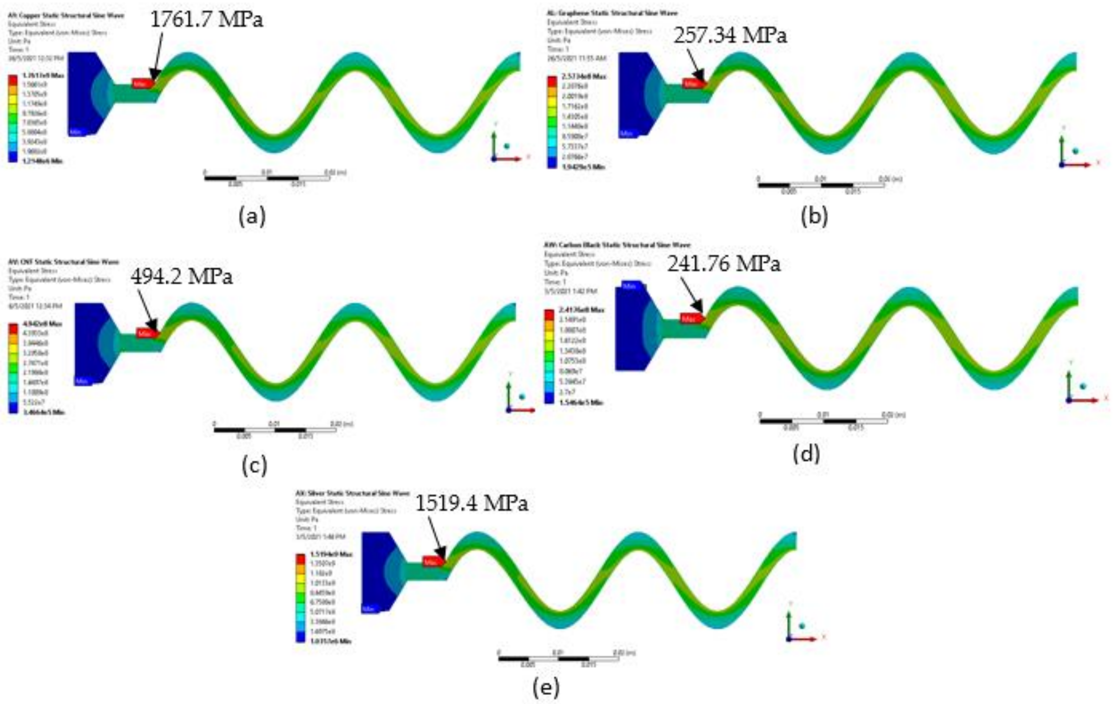

Figure 4. Von-Mises stress of conductive ink. (a) Copper; (b) Graphene; (c) CNT; (d) Carbon black; (e) Silver.

The maximum principal elastic strain for each of the conductive inks was determined using the FEA results, with the assumption that the conductive ink with the lowest maximum principal elastic strain would have the best stretchability value. From the observation in Figure 3, silver conductive ink can withstand more strain than the other conductive inks with 14.938 x 10^{-3} maximum principal elastic strain. By using the maximum principal elastic strain, the carbon black has the largest percentage difference when compared to the copper (baseline) conductive ink, which is about 2.63% less strain followed by graphene 2.24%. This indicates that graphene and carbon black do not show very significant differences in strain and stress values compared to these two materials. As well as carbon-based CNTs have a higher value on strain and stress compared to graphene and carbon black.

The FEA results demonstrate that the carbon black has better stretchability followed by graphene as compared to copper conductive ink. Due to its low price and high conductivity, copper is a common metal-based material for conductive ink applications [34]. However, copper use is limited, because copper nanoparticles oxidise quickly in the air, compromising its electrical properties [3]. As compared to conductive inks, the resistivity of metal foils is significantly lower [35]. After 20% strain penetration, the FEA reports that the carbon black followed by graphene conductive ink is more stretchable than other conductive inks due to its low strain and stress values. This FEA value is based on an ideal scenario with no ink-to-substrate delamination, no tension cycling, and no variations during the manufacturing process.

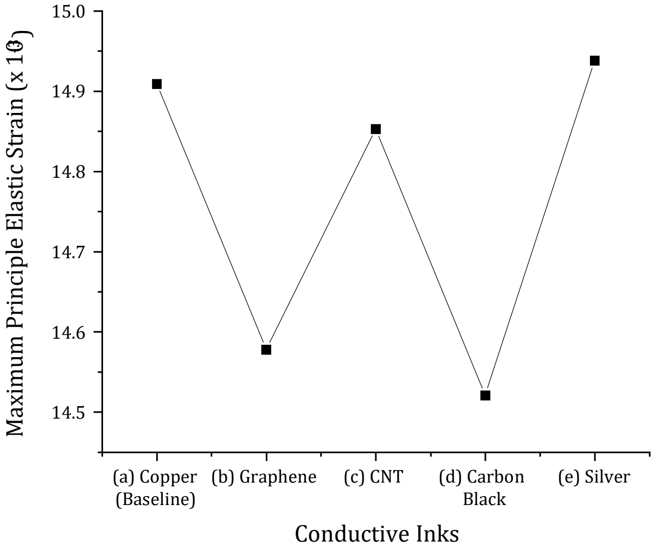

Figure 5. Percentage difference between the graphene (baseline) and other conductive inks using maximum principal elastic strain.

Figures 5 and 6 shows that of all the conductive inks, metal-based, copper and silver conductive ink has the highest maximum principal elastic strain and Von Mises values. As compared to carbon-based conductive inks, this means that metal-based has a very high level of hardness. The high-stress value is due to the influence of metal-based Young's modulus, which is excessively high in comparison to carbon-based materials. According to [15], the higher the sintering temperature and the higher the percentage weight of silver nanoparticles, the higher Young's modulus and hardness of the printed silver sample.

CNT showed the highest values in both experiments, maximum principal elastic strain and Von Mises stress than all other carbon-based materials. According to [36], CNT is theoretically distinct as a cylinder fabricated from rolled-up graphene sheet with a limit on elasticity and some defects in the nanotube's structure, such as defects in atomic vacancies or a rearrangement of the carbon bonds, can weaken the nanotube's strength. Table 3 shows that the results for strain and stress CNT, 14.853 x 10^{-3} and 494.2 MPa, respectively, are not significantly different than the results from [14] research for strain and stress, about 13.5 x 10^{-3} and 1000 MPa, which used the same mechanical properties.

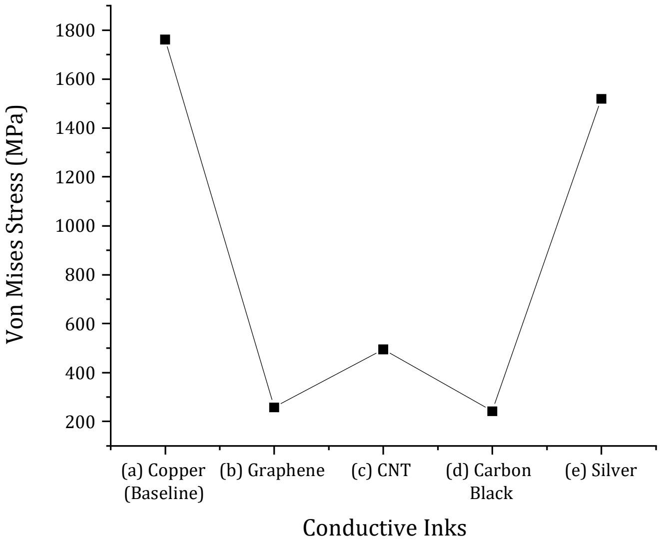

Figure 6. Percentage difference between the graphene (baseline) and other conductive inks using Von Mises stress.

4. CONCLUSION

The study was carried out successfully in demonstrating the optimal stretchability performance of different conductive ink by using maximum principal elastic strain and Von Mises stress analysis. The carbon-based conductive ink carbon black and graphene, 14.521 x 10^{-3} and 14.578 x 10^{-3}, respectively, produced the best results in terms of maximum principal elastic strain as a percentage difference from copper (baseline), with percentage values of 2.63% and 2.24%. Carbon black and graphene, with Von Mises stress values of 241.76 MPa and 257.34 MPa, respectively, have the highest percentage difference as compared to copper (baseline), which has between 7 and 6 times less stress. The findings show that carbon black can be an alternative to graphene as a good conductive ink in mechanical behaviour. This also validates Young's modulus values influencing the materials' strain and stress behaviour. The results also showed that FEA modelling could be used to develop the best screen-printed conductive ink for stretchability and that the maximum principal elastic strain could be used to estimate the increase in resistance change during stretching.

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