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A Review on Electrical/Thermal Characterization Properties of Some Selected Conducting Materials

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ABSTRACT

Technology breakthroughs have driven the shrinking of electronic devices in recent years, not only in the well-known sector of Internet Works, but also in other fields such as flexible and textile electronics. Many suppliers have already begun producing and bringing to market conductive threads that can be used by researchers and the general public for their works, as the latter forms a great ecosystem for new devices that could be functional such as heating garments or sensory. However, no detailed assessment of the electrical performance of such threads has been done so far, and that is what this study aims to change or bring out. Four commercially available threads from two separate vendors were put to test in order to determine their maximum power handling capabilities, both continuous and instantaneous. They were then investigated at a microscopic level to see whether there were any design flaws or hidden restrictions. For each of the four threads, a preliminary profile/study was successfully established.
Keywords: Conductors, Materials, Electrons, Metals, Conductive thread, Metallic bonding

INTRODUCTION

Conductors are materials that allow electrons to travel around freely [1,2,3]. Metals like aluminum, copper, silver, and gold are the most common examples. Because of its great conductivity and inexpensive cost, copper is the most popularly used material for any conductive purposes [4,5,6]. Silver is an excellent conductor, but too costly to use on regular basis. The human body and all salt water are also excellent conductors [7,8]. Electrons do not travel at the speed of light when they pass through a conductor, and on the other hand rarely move very far, instead, each electron gently pulls its neighbor. The next electron is pushed by each other and so on. That's how it works with electricity. The electrons in direct current systems (DC) keep pushing each other through the machine [9]. In alternating current (AC) systems, electrons push each other one way before returning the other way. Because electricity flows in various ways through AC and DC conductors, different systems are utilized to make each one as efficient as possible [10]. The field of stretchable electronic systems has seen a surge of interest in the recent decade making researchers and market participants drawn to this field not only because of the unique opportunities to work with a variety of materials such as paper, textiles, and plastics, but also because it allows for the construction of devices with exceptional comfort, compatibility, fit, and deformation [11]. Despite the fact that this field of study is still in its infancy, work has been presented in which sensing elements, new production ideas, and design have been flawlessly combined to create wearables that do not alienate their users and integrate in readily with their everyday uses/opportunities [12].

As a result, devices require materials that outperform the mechanical capabilities of thin films, which are typically used in printed circuit board design, via an emerging new sector based on the integration of textiles, namely conductive threads, to create the so-called e-textile domain [13]. There is no reason to believe that conductive threads are the only way to make e-textiles; there are other options, such as using metallic interconnects using lithographic techniques, screen printing [14], micro dispensing [15], or even inkjet printing [16]. However, while such systems are efficient at conserving materials, they may not be the best choices for making long-lasting e-textiles due to the severe and uneven roughness of woven materials, wicking phenomena, and abrasion due to washing chemicals. Alternatively, if the textile or garment's extra functionality is provided by its own threads [17], it is projected to have a significantly longer usable lifetime. The concept of producing electrical fibers that can be used to make threads has already been thoroughly investigated. In [18], silver was used to coat nylon and cotton threads of various densities, as well as polyester and polyester/rubber combinations. PEDOT: PSS-coated conductive fibers were manufactured and found to be around 10 times less conductive than Ag-coated counterparts in Reference [6]. Finally, in [8], the researchers are using commercially available polypropylene yarns to prevent short-circuiting in a variety of situations, including submersion in water. Friction spinning is used to wrap polypropylene fibers around Ag-coated polyamide yarns, which is then melted in an oven for binding purposes. Researchers have mostly focused on the impact of adverse conditions on fabrics, such as different types and classes of stitching (Ruppert-Stroescu and Balasubramanian, 2018), successive abrasion [11], or repeated washing cycles [13] as well as the effects of chemicals employed as detergents or ironing agents [10]. However, little information has been provided on how the conductive thread itself can handle power and how this can effect it [15]. Furthermore, there is a scarcity of information in the open literature or in thread manufacturer catalogs concerning the maximum electrical current or voltage that may be applied to conductive threads, which is extremely useful information from a practical standpoint. Hence and in view of this work, we reviewed the electrical characterizations of conductive threads for textile electronics.

Metallic bonding

Metals generally are so good at conducting electricity because of how metal atoms chemically bond. This is called metallic bonding. The table is to help in understanding metallic bolding.

Table 1: Electrical conductivity of materials at certain temperature

Material	ρ [Ω·m] at 20°C	σ [S/m] at 20°C
Silver, Ag	1.59×10^{-8}	6.30×10^{7}
Copper, Cu	1.68×10^{-8}	5.96×10^{7}
Gold, Au	2.44×10^{-8}	4.10×10^{7}
Aluminum, Al	2.82×10^{-8}	3.50×10^{7}

When atoms of metal bond together in a crystalline structure share electrons between them, the electrons are free to conduct if given just a little energy in the form of heat, light, or voltage. So when we apply even a small voltage (like a small battery) to a metal, its electrons begin to flow toward the positive terminal of the battery or voltage source. Silver, copper, and gold all have only one electron in their outermost electron shell, called the valence shell in alliance that electrons stay bonded to an atom because the positive charge of protons attract the negative charge of the electron.

In silver, copper, and gold, there is only one electron at the farthest point from the positive charges (protons) in the atomic nucleus which is relatively far from the positive charge of the nucleus, which is screened by the other non-valence electrons that are between the nucleus and valence electrons. Therefore the valence electron in the metals tend to have a weaker bond to the nucleus than atoms with other electron configurations.Each atom in a block of silver, copper, or gold, contributes one electron that is available for electrical conduction. These electrons are relatively free to drift in a phenomenon called the 'electron sea'.While some metals are excellent conductors, all metals in the real world have internal structures that prevent perfect conduction. Defects are imperfections and can be found in every piece of metal in the real world. Defects cause electrons to scatter as they travel through the material, preventing optimal conduction. Luckily, it's easy to produce conductors like copper that have 'good perfect conduction even if imperfect. We cover this issue in much more detail in our lesson on electrical resistance.

Conductive Threads

Conductive thread can carry current the same way wires do, which means it can be used to create a circuit. This allows the user to sew a circuit together, creating flexible circuits that require no soldering. In some textile-based projects, this is the most practical tool to maintain the hang of the fabric, it's a very safe and unintimidating way to learn how to use embedded electronics. SparkFun currently sells silver and stainless steel threads. Beyond our selection of conductive threads, there exists a staggering number of conductive materials. If it's electrically conductive (you can check this with a multimeter), and you can sew with it (this includes hand and machine, sewing and embroidery, crocheting, knitting, all sorts of such), It is encouraged to consider it a conductive thread. Some traditional embroidery threads have enough metal content to be conductive, and some wires are fine enough to sew with.

Electrical Characterization

Electrical characterization is a collection of measures carried out by electrical engineers to ensure signal quality on a PCA. This test involves using an oscilloscope to measure interconnect signals and buses to ensure that they fulfill component requirements, and it should be done early in the prototype phase, right after bring up. Because firmware is often not yet completed, you must employ development probes and methods to exercise the interconnect signals so that you can measure them because of the early time period. It is, nonetheless, a vital test since it can reveal design flaws, marginal signals, and other difficulties that can lead to a lot of wasted time and money in the future.

Electrical Characterization Techniques

Electrical characterization can be used to determine resistivity, carrier concentration, mobility, contact resistance, barrier height, depletion width, oxide charge, interface states, carrier lifetimes, and deep level impurities. The following are the techniques of electrical characterization of materials.

- Two-point probe
- Four-point probe
- Differential Hall effect
- Capacitance voltage profiling

- Deep-level transient spectroscopy (DLTS)
- Electron beam-induced current
- Drive-level capacitance profiling (DLCP)

MATERIALS AND METHODS

Materials

Four different commercially available threads were investigated for this study. MADEIRA Garnfabrik (MADEIRA Garnfabrik Technical Datasheet HC 12, 2019; MADEIRA Garnfabrik Technical Datasheet HC 40, 2019) provided HC 12 and HC 40, which were both made of 100% Polyamide/Silver plated yarn. Without silver coating, HC 12 has a thread count of 2352dtex and 610dtex 15 dtex with silver coating. HC 40 is from StatexProduktions- und Vertriebs GmbH's Shieldex® series and has a thread count of 1172 dtex without silver coating and 290dtex 6dtex with silver coating. AMANN Group (AMANN Group AMANN TechX Brochure) supplied the two remaining threads (Silver-Tech 50 and Silver-Tech 120), which are part of their Silver-Tech line. The electrical characteristics of all four threads are summarized in Table1. The threads acquired cover the bulk of the manufacturer's catalogs, and these two producers account for the majority of the Serbian market.

Table 2: Electrical Properties of the Supplied Threads

Thread	Electrical Resistance (Nominal)
HC 12	<100 W/m
HC 40	<300 W/m
Silver-Tech 50	<150 W/m
Silver-Tech 120	<530 W/m

METHODS

Governing Theoretical Principles

The threads had to unavoidably become a component of a circuit in terms of electrical characterization. Despite the fact that they are designed to act as wires or transmission lines in practical applications due to their high resistivity values, they will be investigated as resistors. In that sense, a simple voltage divider, consisting of a known-value resistor and a piece of thread placed in series between two sites of potential difference, can be a capable circuit for measuring their real resistance. The key phenomenon in which the threads play a prominent role is Joule heating, which occurs when they function as resistors in Direct Current (DC) or low-frequency Alternating Current (AC) (also termed Ohmic heating or resistive heating). DC circuits are more popular in consumer electronics, thus we'll concentrate on DC characterisation in this work. The power of heating generated by an electrical conductor, P(W), is proportional to the product of its resistance R(W) and the square of the DC current I(A), according to the Joule-Lenz law, and the entire material is impacted.

Design of Experiment

Given the foregoing considerations, a 51 centimeter sample was obtained from each of the four threads. After the experiment, a healthy sample was chosen at random to be inspected under Scanning Electron Microscopy (SEM) to compare its state to that of the electrically burned thread. There were two sections to the experiment. As part of a voltage divider circuit, 25 samples of each thread was subjected to a continuously increasing voltage, until they broke. At a rate of 0.1 V/sec, the voltage was raised. In the second part, twenty-five samples of each thread was sequentially placed in a voltage divider circuit, but this time the rise in voltage was stepped up and sustained for 60 seconds at a time until they reached their breaking point.

Simulation Setup

For each type of thread, a model of the 1-centimeter-long thread was created in 3D using Autodesk's Autocad software, taking into account the number of threads in each filament, the number of twists, their optical diameters, and other properties derived through experimentation or supplied by the thread manufacturers. The thread model was imported as the main geometry into COMSOL Multiphysics and materials will be added to it to allow for the physics investigation. Polyamide 6.6 will be added to the individual fibers, and the Silver plating was added as a boundary condition because its thickness is so little in comparison to the polymer core thickness. This modification allowed conductive surfaces to be created just on the exterior of the individual strands. Because some of the threads include non-conductive parts, special care was required when applying the silver and choosing the physical interfaces to ensure that these boundaries were not crossed. The model was investigated cross-sectionally in a 2D geometry because of its considerable complexity, which included individual silver-plated fibers spun together in groups and more than one of these groups spun together into the thread.

RESULTS DISCUSSION

Thread Electrical Performance

The first question to be answered was whether or not the nominal resistance values provided by thread manufacturers (Table 1) could be validated. The reason for this was because, unlike typical resistor components or cables, none of the threads came with a predetermined value of resistance and a tolerance percentage, but instead came with a wide range of values. The first stage in this project was to compute each sample's individual resistance and extract the average value per thread type qualitatively. This was accomplished using the VI approach, which entails reading the voltage across and current intensity through the sample and calculating the resistance using Ohm's equation. The average resistance of each of the five sets of samples, as well as the standard deviation of each group are shown in Figure1. Except for the Silver-Tech 120, all other threads showed rather consistent resistance between samples which is to be anticipated if the material is homogenous.

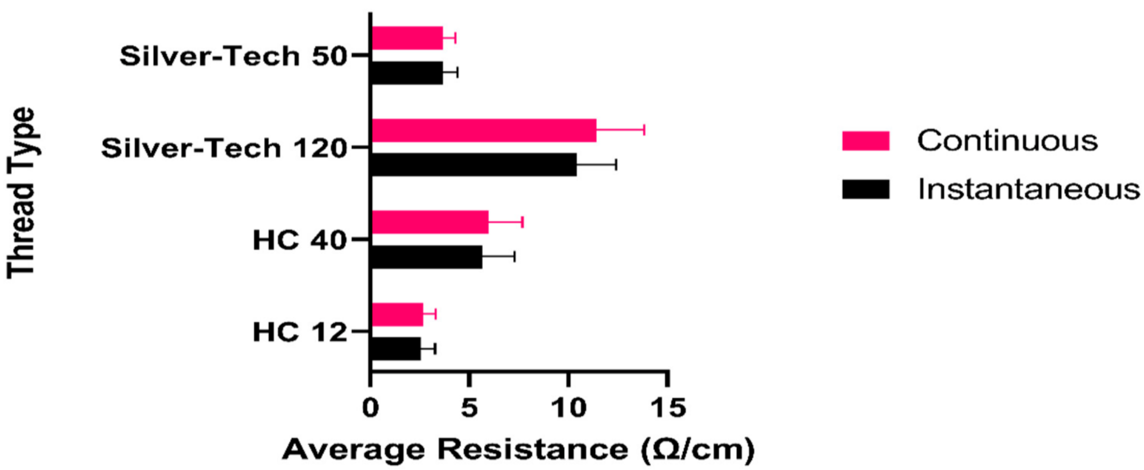

Figure 1: Average measured resistance per thread and per mode of test

Furthermore, the average resistance values in the instantaneous voltage increase mode are slightly lower in all four situations than in the incremental voltage ramp-up mode. This can be explained by the fact that the threads in the second scenario had more time to heat up gradually. Given that any material's resistance varies with temperature and may be approximated as a linear relationship. It's safe to assume that all of the threads had a positive temperature coefficient (PTC). The concentration of silver incorporated around the polyamide core of the threads can be adjusted to control the PTC effect.

Table 3: CalculatedResistanceValuesoftheSuppliedThreads

Thread	Nominal R (Ω/cm)	Min R (Ω/cm)	Max R (Ω/cm)	Average R (Ω/cm)
HC 12, instantaneous	<1	1.02	1.28	1.18
HC 40, instantaneous	<3	2.34	3.11	2.74
Silver-Tech 50, instantaneous	<1.5	2.11	2.39	2.31
Silver-Tech 120, instantaneous	<5.3	7.64	13.06	9.32
HC 12, continuous	<1	1.24	1.54	1.4
HC 40, continuous	<3	2.78	3.31	3.14
Silver-Tech 50, continuous	<1.5	2.67	3.14	2.81
Silver-Tech 120, continuous	<5.3	7.19	13.47	9.98

Another intriguing discovery is the performance discrepancies amongst the four threads studied, particularly between those belonging to the same family. Figure 2, depicts the threads' performance for their mean maximum attainable power before failure. It was clear that all threads could handle higher instantaneous power than continuous power, which was consistent with the effects of Joule heating. These effects eventually lead the material's temperature to rise to the point where it will fail over time. Even though HC 12 and Silver-Tech 50 appeared to have more power in the continuous setting, this was not the case because their standard deviation margins increased significantly compared to the instantaneous setting, and such a claim cannot be generalized.

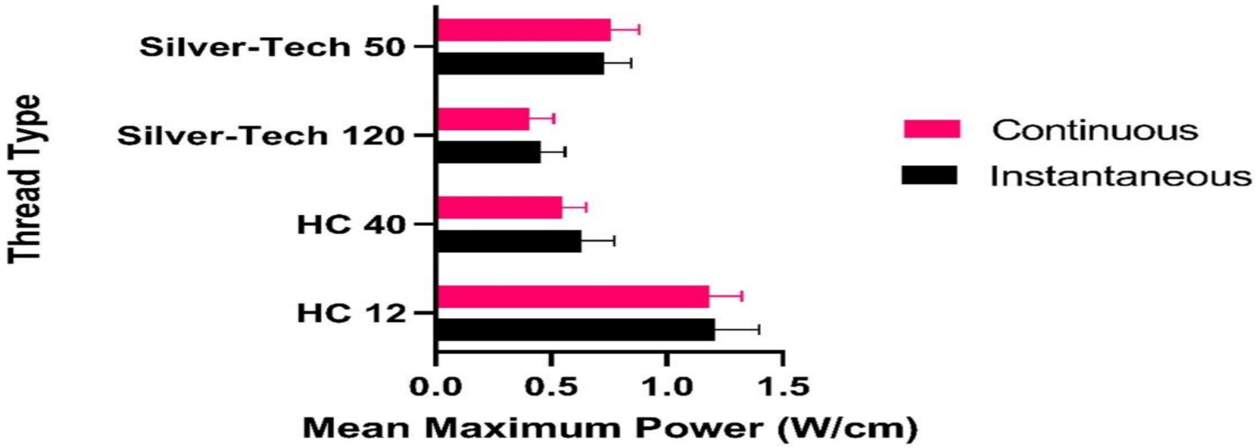

Figure 2: Mean maximum power attained per thread and testing mode (Adrian *et. al.*, 2021).

Another interesting discovery was that the Silver-Tech 120 thread was the most variable of all, with individual samples showing variations in maximum power sustained of up to 170mW. As a result, greater attention should be exercised when designing delicate electronic circuits that rely on that thread. Because four distinct threads were used in a voltage divider circuit in the experiment design, it's useful to look at them for input voltage from 0V to their registered break-down voltage. As shown in Figure 3, each thread fails in a specific range, giving the end-user nearly complete coverage of the voltage range from 0 to 17V. That is captured with the circuit shown in Figure 1 and can be modified with the remaining circuit pieces as needed. It was nonetheless a surprise discovery, because no matter how different the threads' power handling capabilities were, with the four tested, a complete voltage spectrum could be covered without interruption. This is a significant benefit since the voltage and power can be altered simply by sewing a different thread to an unchanged circuit. For clarity, only voltages somewhat near to the failing point of each samples have been displayed in Figure 3, with the exception of Silver-Tech 120. Finally, it was encouraging to observe that the changes in mean sustained power between the two modes for each fiber were minor, with Silver-Tech 50 having the largest difference of all, at 35.5mW. When compared to the individual mean values recorded, 551mW for instantaneous operation and 586mW for continuous operation, this was still less than 10%.

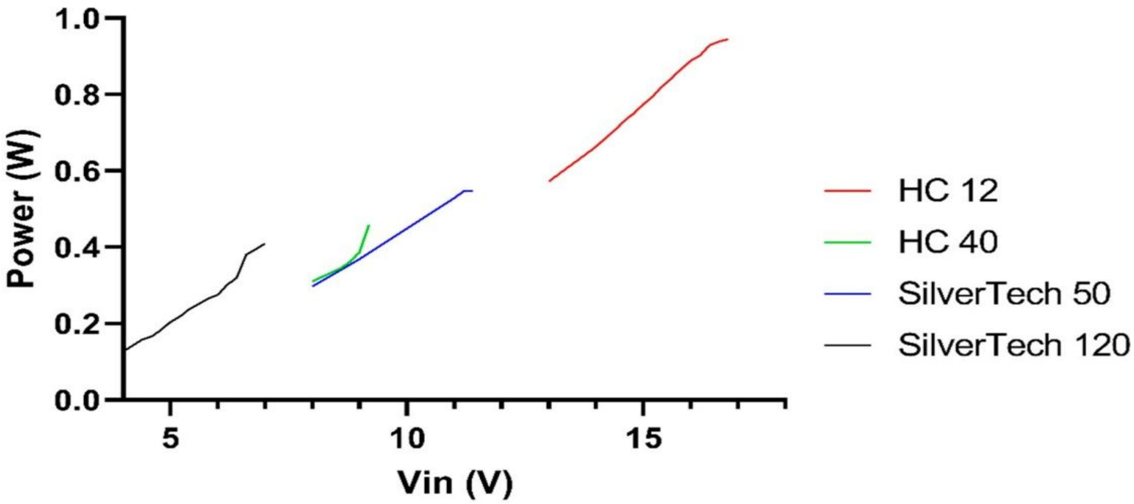

Figure 3: Averageattained power per thread typefor input voltage at the divider depicted [3].

Thread Structural Behavior

Considering, the threads' electrical performance, pushing them to their limits caused severe structural damage, which was detected visually during the experiment and later evaluated under a scanning electron microscope. The important take away from the visual observation was that all of the threads on display were beginning to compress along their length axis as they approached failure. This behavior is summarized in Table 4. This led to the theory that all of the threads failed not because they reached their absolute limits, but because they were anchored on both sides to the crocodile clips that provided the potential difference, causing them to physically break in half.

Table 3: Summaryofthemeasuredcontractionofthreadspost failure (Adrian *et. al.,* 2021).

Thread	Min Contraction (mm)	Max Contraction (mm)	Mean Contraction (mm)
HC 12, instantaneous	0.4	2.6	1.2
HC 40, instantaneous	0.1	2.1	0.7
Silver-Tech 50, instantaneous	0.2	1.8	0.4
Silver-Tech 120, instantaneous	0.2	1.6	0.6
HC 12, continuous	0.3	2.2	0.8
HC 40, continuous	0.2	1.7	0.6
Silver-Tech 50, continuous	0.2	1.7	0.3
Silver-Tech 120, continuous	0.2	1.4	0.6

This finding does not undermine the experiment's findings, because the time interval between the threads contracting and the actual separation was incredibly short, and because after experiencing such considerable damage, it was evident that such a thread would not be utilized as intended again. It's worth noting that the contraction was permanent, as the threads' original length was never restored after removing the applied voltage, even before they failed. Although this may be due to the materials and procedures utilized in the manufacture of such threads, such research is beyond the scope of this project.Figure 4 shows a healthy Silver-Tech 120 thread sample, which was cut from the same yarn as the samples utilized in this work's electrical characterization. The presence of a significant amount of silver plating delaminating, which may be related to the thread's electrical behavior's volatility, was a startling observation. Due to probable unintended abuse during sample handling and loading, the sample was rigorously checked along its length to ensure that such surface irregularities were present throughout its length and not just in this random area. The results showed that this image accurately depicted the entire 1cm length of the sample. Furthermore, as shown in Figure 4, study on the damages that threads have received from the time they are manufactured to the time they reach a final consumer should be carried out. Even before any experimentation, a SEM photograph of the healthy and electrically unused thread confirmed the presence of severe silver plating delaminating. It's reasonable to assume that this thread's electrical behavior will be influenced by its volatility and structural flaw. This could be linked to damages incurred after the consumer uses the threads to create a finished product, bending, stressing, and embroidering them.

Figure 5 depicts the same type of thread after it has failed. The thread has physically split, and the entire structure has now created a single object at its terminus. The fibers that used to make up the threads have all but vanished in a single blob of molten polymer. The fascinating part is that under SEM, polyamide and other polymers appear dark grey/black, whereas there is evidence that the molten polymer has partially consumed the silver plating near the point of separation.

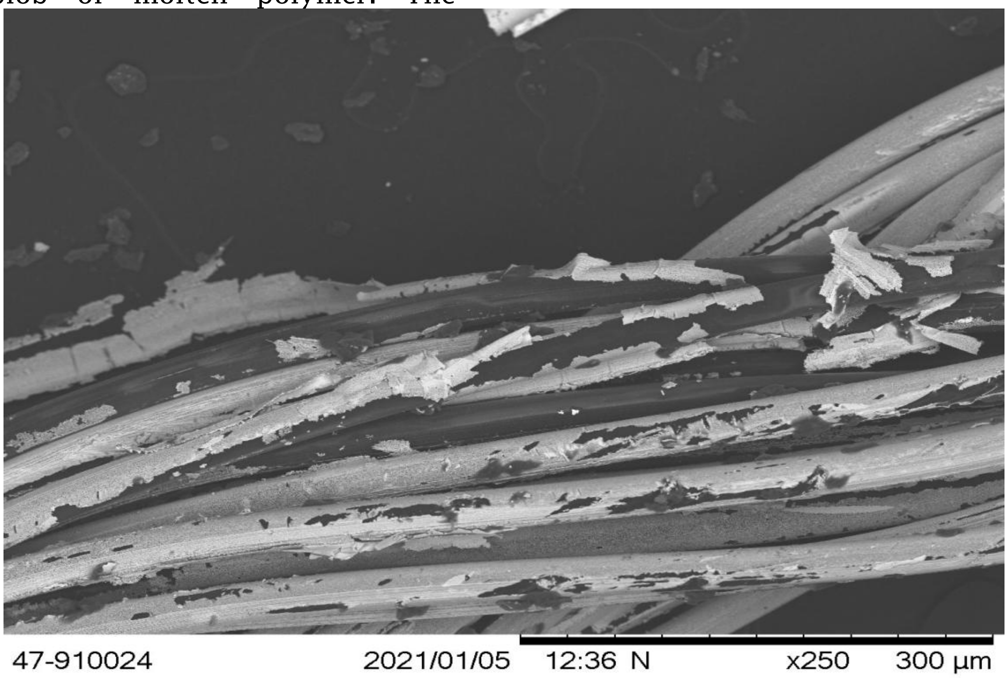

Figure4: SEM image of a healthy Silver-Tech 120 sample, with obvious severe de-plating of the silver conductive layer (Adrian *et. al.,* 2021)

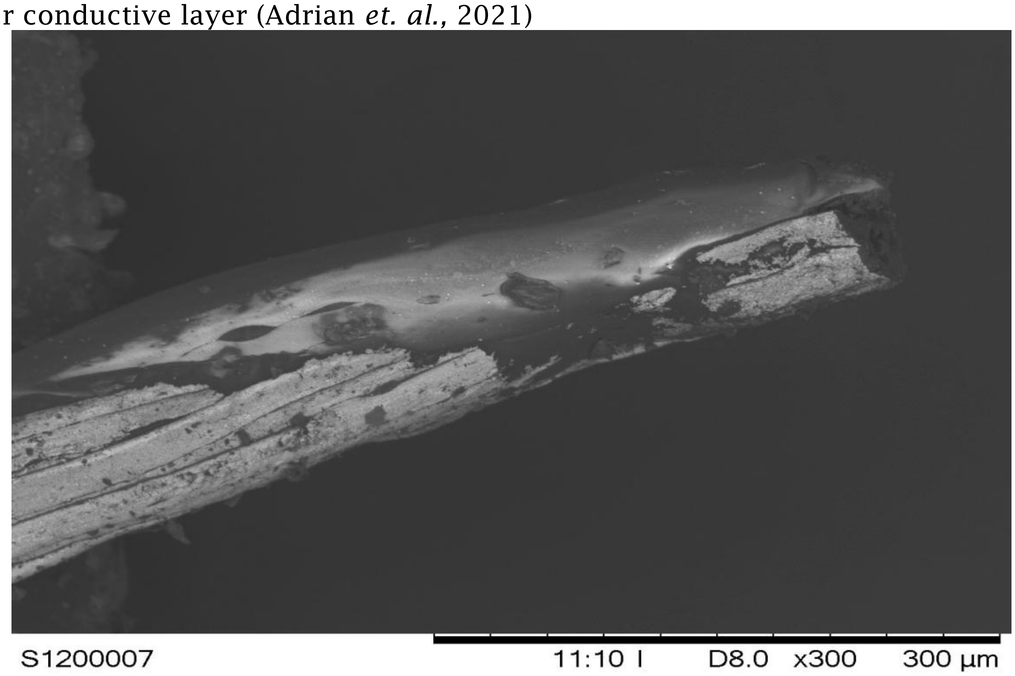

Figure5: SEM image of the failed Silver-Tech120 specimen, where the individual fibers have molten together (Adrian *et. al.,* 2021). Thermal camera (TI160, ULIRVision) was pointed at the thread samples during the experiment to provide insight into the

temperatures recorded at the time of breakdown. Table 4 illustrates these results per thread type, as the threads failed at comparable temperature values in both the instantaneous and continuous modes of testing. Because these temperatures are slightly lower than the glass transmission temperatures of the polymers utilized in the fiber core, this is to be expected. This indicated that the threads were failing structurally rather than electrically, as rising temperatures in the core made them mushy and bendable, and they split under the influence of gravity (as catenaries).

Table 4: Temperatures recorded per thread type at the time of failure.

Thread	MinTemp(°C)	MaxTemp(°C)	AverageTemp(°C)
HC12	42.6	53.7	47.14
HC40	41.5	54.2	48.92
Silver-Tech50	53.3	58.3	56.4
Silver-Tech120	35.6	49.2	46.3

CONCLUSION AND RECOMMENDATIONS

Summarily, the purpose of this study was to investigate the electrical properties of commercially available conductive threads, given that their producers only provide a nominal value for electrical resistivity. Ten samples of each thread were employed as a device under test, each constituting part of a voltage divider circuit with a specified value resistor. Five of them had their voltage quickly increased to their breaking point, and five of them had their voltage increased in 60-second increments. There were three noteworthy outcomes. The fact that each sample of the same thread has a significantly varying resistance, which does not match the nominal value stated. Secondly, the fact that each thread can support more power for a shorter period of time than continually is consistent with the physics of electrical circuits, resistive heating, and convective heat transfer. Finally, and perhaps most crucially, the manner individual thread samples have been damaged varies, even among samples from the same series or family of threads. The importance of additional research into the thermal characterization of threads is highlighted by the last observation. Furthermore, study of the damages that threads have received from the time they are manufactured to the time they reach a final consumer should be undertaken. This could be linked to damages incurred after the consumer uses the threads to create a finished product, bending, stressing, and embroidering them.

CONCLUSION

This research reviews that, while the four studied conductive threads can sustain a significant amount of power for a long time, users should proceed with caution because their performance cannot be standardized at this time, and their usability for precision applications may need to be further evaluated. Individual threads' power capacity, on the other hand, may make them perfect candidates for woven/embroidered antennas or sensors.

RECOMMENDATIONS

Despite the fact that this study found that the four investigated conductive threads can withstand a significant amount of power before failing, the experiment was carried out with free-standing threads, as reviewed in this study. As a result, a fascinating potential future development would be to perform the experiment using threads that have already been stitched to a fabric or substrate, removing their convective properties. Furthermore, this discovery is essential for other researchers working in the field of flexible and stretchable electronics since it gives critical information on the electrical limits of the threads utilization. This will ensure that more reliable circuits are created if the electrical threads employed are within safe limits and respond as predicted; thus, comparable electrical characterization of additional threads can be accomplished in the future. Another question to consider is how much heat the wearer can endure, presuming the thread is part of a wearable device that comes into direct contact with the skin. It's possible that the threads' maximum current carrying capacity won't be utilized in this situation. As a result, more future study in general thermal characterization of such threads is advocated, which will provide observations that will aid designers of textile electrical circuits in achieving higher dependability and stability of predicted performances.

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