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Industrial Recycling of Scrap Copper Cables and Wires: Combining Cold and Hot Treatments for Maximum Recovery and Minimal Emissions

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Abstract

With the increasing amount of electrical cable and wire scrap, copper recycling has become a priority to conserve natural resources and reduce environmental impact. This study presents an innovative process for recycling copper wire and cable of various types, including greased ones. The process combines cold and hot treatments to maximise metal recovery while minimising polluting emissions. Initially, the cables are stripped and the PVC sheaths and other components are separated. Subsequently, these cables are subjected to pyrolysis in a hermetical furnace operating under an inert atmosphere, ensuring the absence of toxic emissions.

The pyrolysis, carried out at temperatures between 500 °C and 600 °C, decomposed the insulating materials while minimising copper oxidation. A 100 kg sample of wire and cable pyrolysed at 540 °C was melted in an Indian foundry using the Upcast process to produce 8 mm oxygen-free copper rods. The electrical conductivity measurement of these rods showed a value of 98.2% IACS, making them suitable for many applications, especially electrical ones. The copper recovery rate reached a maximum value of 99.5%, demonstrating the effectiveness of the process. This sustainable process, suitable for small and medium foundries, offers an efficient and environmentally friendly solution for copper cables recycling.

Keyword: Copper recycling, Greased cables, Cold treatment, Pyrolysis process, Greased cables, Upcast process

1. Introduction

The circular management of natural resources is essential to ensure their long-term availability. The application of recovery and recycling technologies will play a central role in promoting sustainable development worldwide [1-2]. The rapid development of the energy and information technology (IT) sectors has contributed significantly to the increased production and use of cables, which consume a significant proportion of the world's copper [3-7]. This growth has led to an increase in cable scrap, for example in Germany over 150,000 tonnes are generated annually [8]. This highlights the importance of recycling these materials to conserve resources and protect the environment [9-10].

In addition to enamelled wires, copper cables recycled by most non-ferrous metal foundries are classified into five categories according to their manufacturing process, functions and usage characteristics: magnetic wires, bare wires, electrical wires and cables, power cables and communication cables [11]. These single-pole or multi-pole cables, with a lifespan ranging from 10 to 30 years, generally consist of a conductive, insulation, auxiliary element, mechanical protection, shielding, armouring and PVC outer sheath [12-13]. The conductor core is made from industrially pure copper or oxygen-free copper with a purity of over 99.90%, with excellent electrical and thermal conductivity and excellent chemical stability, and accounting for 58.3% to 75% of a cable's total weight [13-14].

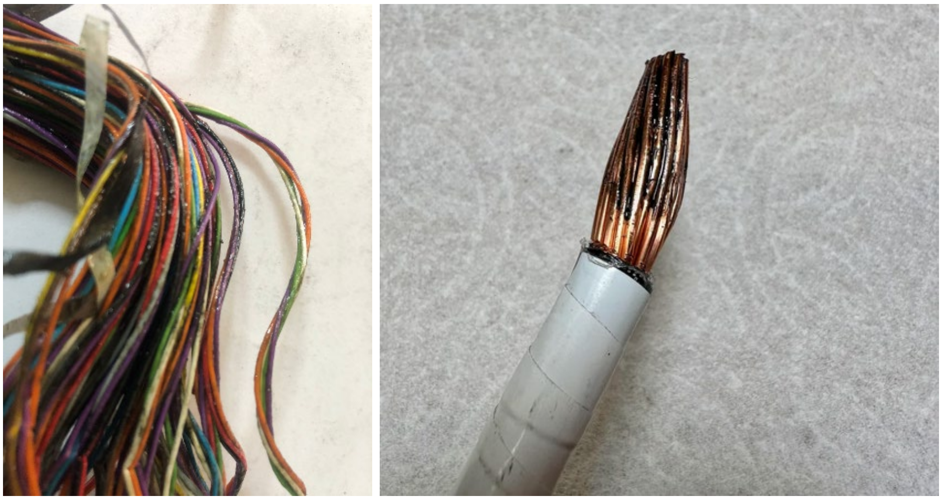
In addition to incineration, a traditional method of waste recycling involves open combustion, where the copper fraction is recovered from the remaining ashes [14] and the burned plastic residue releases energy [15] as well as toxic gases into the environment [16-17]. Semi-mechanized or mechanized processing techniques are used to separate copper from the insulating layers of large diameter cables, which have stable composition and uniform specifications [18-19]. Specific techniques are used to recycle mixed type cables with different compositions of insulating layers and intermediate or small diameters. These multi-step techniques generally involve mechanical methods (such as the use of ultrasonic [20] or hot water processes [21] combined with a mixer to dismantle the cables, followed by electrostatic separation [22-23], particle size classification [24], flotation [25] or dense separation [13] to isolate plastic and copper components), chemical methods (such as dissolution and cementation[26] , chemical or biological leaching [27] and chloride volatilization [28]) and/or processes of energy recovery (such as steam gasification [14] and pyrolysis [29-31]).

Pyrolysis involves the chemical decomposition or transformation of a material into one or more substances at high temperatures in an inert atmosphere. This process is widely used to recycle enamelled wires and copper cables, as it enables the recovery not only of the metals but also of their protective elements (sheaths and insulators) [1-32]. The sheaths, mainly made of polyvinyl chloride (PVC), must be processed carefully during disposal to minimise the negative effects of their components, such as lead (Pb)-based stabilisers, phthalate plasticisers [33], mercury (Hg), cadmium (Cd), hexavalent chromium (Cr (VI)), polybrominated biphenyls and polybrominated diphenyl ethers [34]. In addition, the pyrolysis of PVC releases toxic organohalogen compounds and generates large quantities of hydrochloric acid (HCl), which can cause material damage and pose serious environmental problems [35].

The plastic-to-metal ratios of electrical cables are typically ~ 45% and ~ 55% by weight, depending on their use and specifications [1-36]. Previous studies [1,8,14] have reported recycling recovery rates ranging from 95 % to 99.85 % for certain types of cables, including cable bundles with diameters between 0.5 to 2.5 cm and tinned copper. These studies involve expensive specialised equipment and techniques that make industrialisation challenging [37-38]. To improve the copper recovery rate and the level of purity obtained, this study will test a pyrolysis recycling process accessible to small foundries. This economic and Low environmental impact process will treat all types of copper wire and cable in large quantities, including those containing grease and oil, which are difficult to recover.

2. Methodology

A 100 kg batch of copper wire and sheathed cables was randomly selected from the copper scrap commonly received by Bonomar Company, specialising in non-ferrous metal recycling. The batch, consisting of enamelled wires and various cables for the transportation of electrical voltage or communication, was manually sorted by qualified operators based on multiple criteria such as dimension, shielding (steel or aluminum), grease (Fig.1), and other physical characteristics. These cables were then cut into one to two meter lengths using hydraulic and mechanical shears, and classified into different categories:
- A: Greased wires of various diameters.
- B: Greased cables with shielding (steel or aluminium).
- C: Carrier cables.
- D: Groove.
- E: Sheathed cables (without shielding or grease).
- F: Fibre-optic cables.



(a) (b)

Fig.1. Greased cables a) greased wires, b) greased wires with shielding

2.1. Cold treatment

Class A, B and D cables are then stripped using a stripping machine, which separates the PVC sheath from the internal metal wires (Fig.2). The stripped materials are then sorted manually by operators on a conveyor belt. They separate the PVC, the shielding, the ceramic paper and the copper wires. The grease present on some cables partially sticks to the wires and the insulation. PVC, class F cables and metal components such as steel or aluminium shielding are separated and sent to specialised units. Enamelled wires and those covered with plastic and grease are placed on a grid and pyrolysed in an furnace. Class C cables are not treated with this treatment.

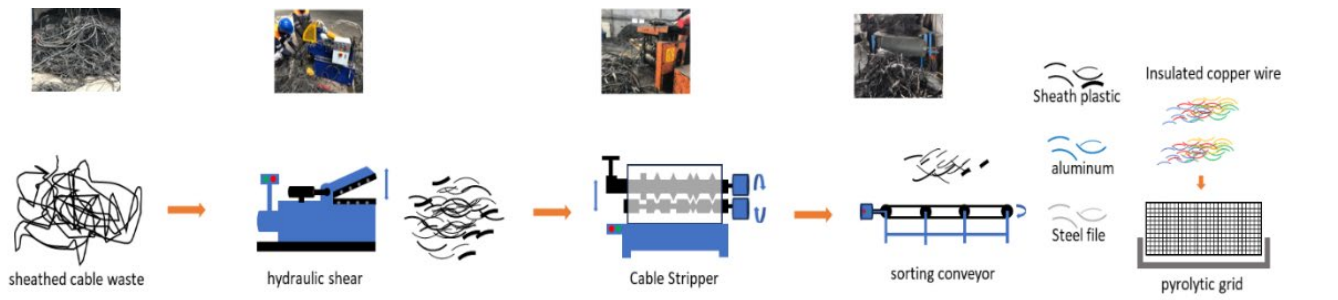


Fig.2. The Stages of Cold Treatment

2.2 Hot treatment (Pyrolysis)

The pyrolysis process (Fig.3), lasting between 90 and 140 minutes, begins with the insertion of the grid into the furnace. This hermetic furnace, with a maximum capacity of one ton and a total power consumption of 45 kwh, designed to operate on solar energy and prevent gas emission.

Before starting the heating process, the furnace is purged with nitrogen from a dedicated generator to establish an inert atmosphere. This purging lasts about 30 minutes, calculated based on the volume of the furnace, with an injection pressure of 10 bars. Once the atmosphere is saturated with nitrogen, the electric heating begins. The furnace temperature is then gradually increased until it reaches the pyrolysis range, between 500 and 600 °C. This furnace is designed to increase the temperature by 16°C every two minutes. During the pyrolysis process, a continuous flow of nitrogen is maintained at a rate of 6 litres per minute to ensure an oxygen-free environment. Heating is stopped when the pyrolysis temperature is reached. The furnace cannot be opened until the temperature has dropped to around 180°C to prevent ignition of the gases and organic residues [39]. After complete cooling, the grid is removed from the furnace and the treated copper wire and cable are recovered. Organic residues (plastic, grease, and powder) fall into a bag at the bottom of the furnace, where they are collected as plates or pieces.

The extracted copper wire and cable is washed with water in a rotating drum to remove any traces of powder. After air-drying, the scrap is compacted into bundles using a hydraulic press. These bundles were sent to a foundry in India to produce 8mm oxygen-free rods using the upcast process.

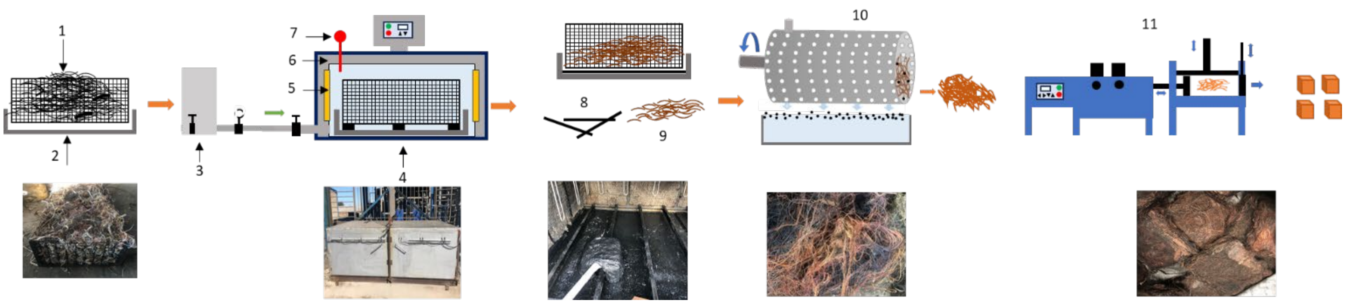


Fig. 3. Stages of Hot Treatment (Pyrolysis): 1- Insulated copper wire, 2- Pyrolytic grid, 3- Nitrogen, 4- Hermetic furnace, 5- Resistor, 6- Insolation, 7- Thermocouple, 8- Organic substance, 9- Copper, 10- Washing drum, 11- Press wire

2.3 Conductivity measurement

The conductivity of these rods was measured by a conductivity meter in a private laboratory. Before each test, this instrument is calibrated with reference samples of known conductivity. Ambient conditions, such as temperature, are measured because they have a direct influence on conductivity.

To test a sample of these rods, it was chemically cleaned by immersion in a dilute acid (sulphuric acid (H_2SO_4) or nitric acid (HNO_3)). After being rinsed with distilled water, the sample is cut to a specific length (often a few tens of centimeters from 100 to 500 mm) for homogeneous testing.

These segments are then connected to a specific electrical circuit via electrodes (from 1 to 100 mA) to measure their electrical resistance (R). Conductivity is then determined by the relationship:

$$\sigma = 1/\rho \text{ with } \rho = R \times (L/A)$$

- R : Resistance (ohms),
- A : Area of the rod (m2),
- L : Length of the rod (m).

3. Results Discussion

3.1 Residue Analysis

In general, the wire and cable pyrolysis process involves two distinct phenomena corresponding to temperature ranges of 300°C to 400°C and 450°C to 550°C [37]. The first range is associated with the dechlorination of PVC sheaths and insulators, during which undesirable hydrogen chloride (HCl) is released due to the thermal decomposition of PVC. This process can be represented by the reaction: PVC → $PVC_{\text{Dechlorinated}}$ + HCl.

At the end of this step, we obtain a less toxic and more stable $PVC_{\text{dechlorinated}}$ residue. In the second temperature range, the remaining organic components in the $PVC_{\text{dechlorinated}}$ begin to decompose further in the absence of oxygen. This decomposition generates several products, including: hydrogen (H_2), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2) and coal (solid residue). This decomposition maximises the conversion of carbon chains into combustible gases, producing mainly light hydrocarbons.

The cold treatment applied to the cables from the beginning significantly reduced the presence of chlorinated materials, particularly PVC, thus minimising the risks of toxic emissions and the generation of hydrochloric acid (HCl). The presence of this acid could lead to corrosion of the furnace and the release of harmful gases, notably organohalogen compounds, posing serious environmental problems [37,40,41]. This treatment has made the pyrolysis process not only more efficient, but also more economical for small foundries.

This is confirmed by the analysis of three samples of pyrolysis residues by X-Ray fluorescence (FX) (tab.1) and ICP (tab.2). The results of these analyses clearly show that most of the elements present in the residues are flame retardants (antimony trioxide (Sb)), thermal stabilisers (based on zinc (Zn), tin (Sn) and lead (Pb)), pigments (titanium oxide (Ti)) fillers (calcium-based calcined clay and calcium carbonate), additives (Al2O3, SiO2 and K2O), mineral fillers (MgO) and secondary phosphorus antioxidants (P2O5) [30,42,43].

Table 1.
Results (Wt. %) of Powder Residue Analysis by fluorescence X (Fx)

	Al_2O_3	C	CaO	Cl	Cu	Fe_2O_3	K_2O	MgO	P_2O_5	Pb	S	SiO_2	TiO_2	Zn
$Test_1$	3.67	48.97	1.59	0.93	1.05	1.82	0.06	0.36	0.2	2.6	0.34	17.19	1.17	0.8
$Test_2$	4.1	41.45	1.32	0.81	0.71	1.77	0.01	0.33	0.2	3.34	0.41	11.68	0.98	0.71
$Test_3$	3.77	47.13	1.63	0.95	0.89	1.81	0.07	0.33	0.13	2.1	0.22	15.77	1.08	0.76

Table 2.
Results (Wt. %) of Powder Residue Analysis by ICP

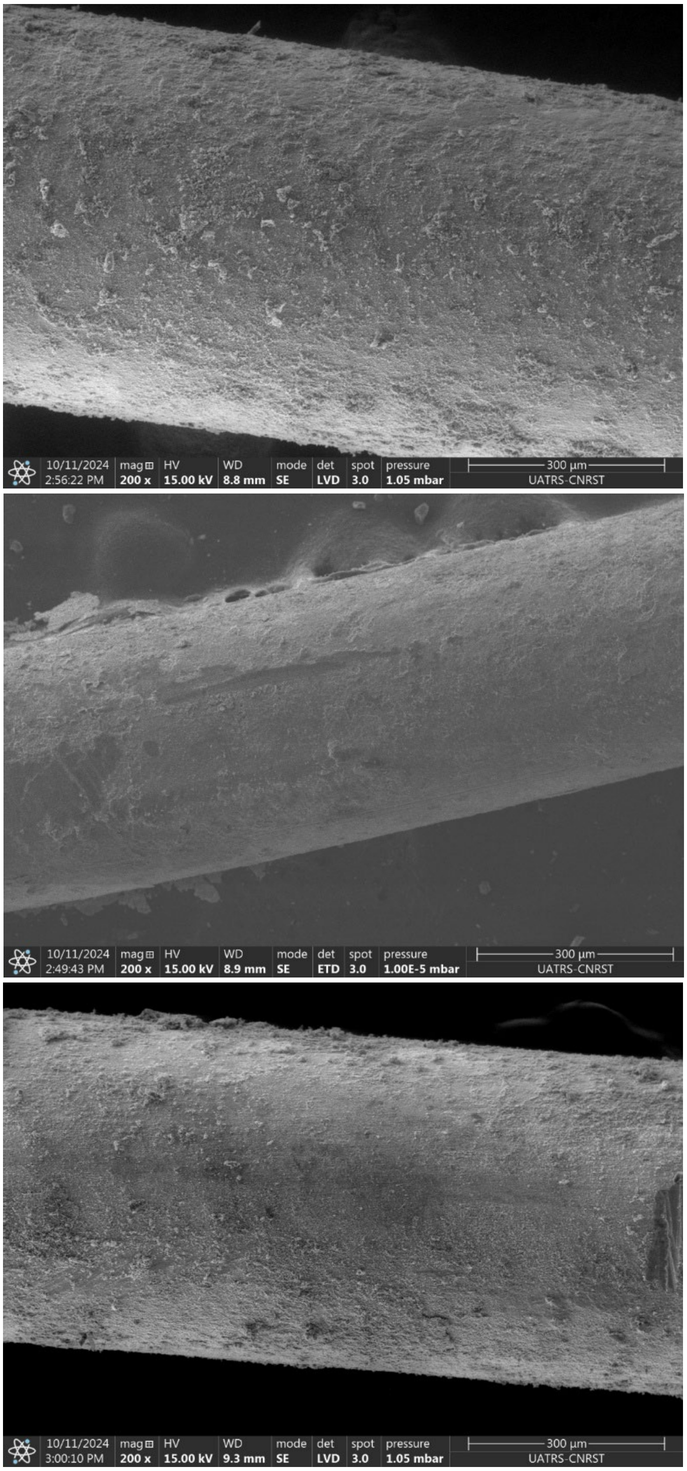
	AS	Li	Mo	Cd	Co	Ni	Sb	Sn	Sr	Y
$Test_1$	<9	<3	<10	2	1	11	14	89	5	3
$Test_2$	<9	<3	<10	2	1	9	13	77	5	3
$Test_3$	<9	<3	<10	2	2	9	14	92	5	3

The low chlorine content of approximately 0.9 wt.%, combined with an ash content of approximately 45.85 wt.% and the presence of non-oxidized metals, gives pyrolysis residues considerable recycling potential. This favorable chemical composition opens the way to various industrial applications, allowing this residue to be used as a secondary raw material. For example, it is sometimes used in applications such as composite material and cement manufacturing [37-44]. The reuse of pyrolysis residues not only promotes the sustainable management of industrial waste, but also contributes to a circular economy by optimizing the use of available resources.

3.2 Pyrolysis product analysis

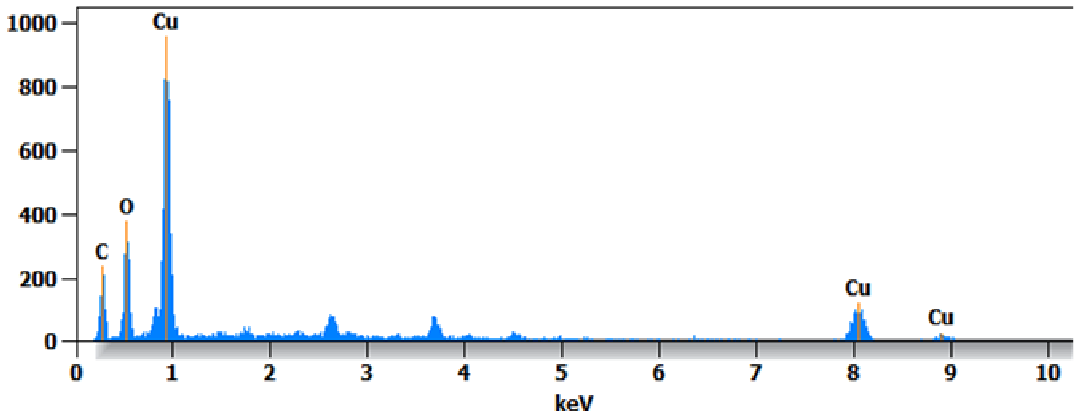
During the pyrolysis process, oxidation of the final product can occur even when working in an inert atmosphere. This oxidation can be caused by the presence of residual oxygen in the oven due to an imperfect seal or to low quantities of oxygen in the inert gas. This can also be attributed to heating, as a small amount of oxygen at temperatures above 600°C can cause significant oxidation of copper.

At the temperature 540 °C, The SEM image (Fig. 4b) of the wire pyrolysed reveals an almost smooth surface, indicating minimal oxidation of the copper. The EDS mapping results (Fig. 5b) show a higher first peak of copper compared to the incinerated wire, suggesting that most of the copper remained in its metallic form. The low oxygen value in this EDS spectrum suggests a controlled atmosphere during pyrolysis, favoring the reduction of copper oxidation. Pyrolysis appears to be an effective method for cable treatment, facilitating optimal copper recovery and minimising losses due to oxidation.

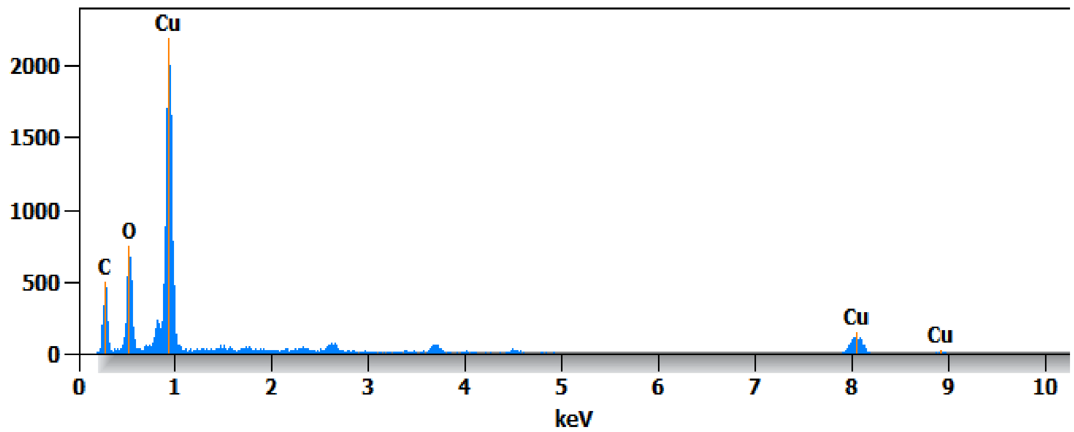


a)
b)
c)

Fig. 4. SEM Pyrolysis products images: a) T=500° C, b) T=540° C, c) T=600° C



a)



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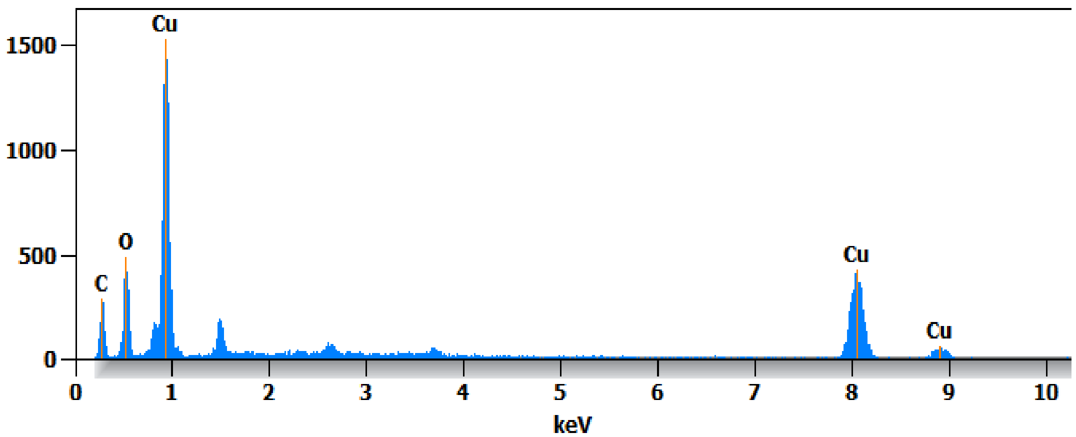
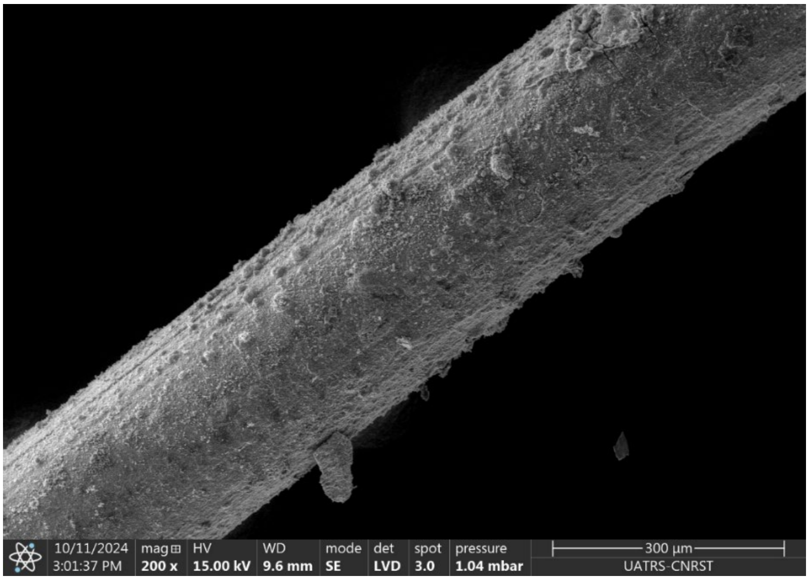


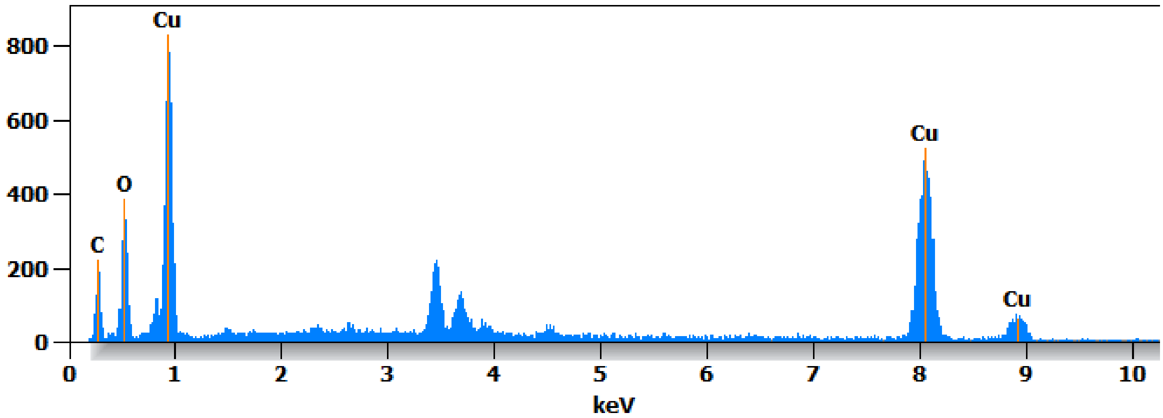
c)

Fig. 5. EDS Pyrolysis products results: a) T=500° C, b) T=540° C, (c)T=600°C

At the same temperature, The SEM image (Fig.6a) of the incinerated wire reveals a rough texture, characterized by the presence of aggregates and particles on the surface. EDS spectre results (Fig.6b) show that the cable contains not only copper, but also oxygen and traces of carbon. Additionally, the presence of three copper peaks indicates significant oxidation after incineration, suggesting the formation of copper oxides such as Cu_2O and CuO.



a)



b)

Fig. 6. Incineration product T=540°C: a) SEM image, b) EDS results

The final pyrolysis product, weighing approximately 100 kg, was sent to a foundry in India specializing in the UPCAST process [46]. After analysis, this product was melted to obtain oxygen-free copper rods with a diameter of approximately 8 mm. The average electrical conductivity of these rods, measured with a SigmaScope SMP10 conductivity meter with ± 0.5% accuracy, is approximately (57.4 ± 0.03) $\times 10^6$ S/m (Tab. 3). The % IACS (International Annealed Copper Standard) value corresponding to this conductivity is 98.2% ± 0.03%:

% IACS = (σ measure /σ copper) ×100 with σ copper= 58.5 MS/m
Incertitude= 98.2 × (0.03/100) = 0.03

Table 3.
Conductivity Measuring Results

	lenght (mm)	Diameter (mm)	Resistance (Ω)	Rsistivity (Ω.m)	Conductivity (s.m-1)
Sample 1	930	7.88	0.0003344	1.80E-05	57019066
Sample 2	650	7.88	0.0002369	1.80E-05	57256666
Sample 3	300	7.88	0.0001059	1.72E-05	58079725

This result indicates that these rods are of very high quality with IACS > 97% and are suitable for the manufacture of electrical cables [46-47].

With a copper recovery rate of 99.5%, this pyrolysis process remains competitive compared to other processes in later studies [14-36] that require special equipment. This efficiency is attributed to the use of a special hermetic furnace, allowing for complete decomposition of organic materials and effective metal separation. As a result, this process, capable of handling all types of cables in large quantities, is better suited for the industrial environment.

4. Conclusions

This study presents an effective and sustainable approach to recycling copper wire and cable, including greased ones. The combination of cold and hot treatments, in particular the pyrolysis process in a hermetical furnace, resulted in high metal recovery while limiting toxic emissions. This process successfully decomposed the insulating materials and achieved a maximum copper recovery rate of 99.5%. Furthermore, the copper rods produced through the UPCAST process from pyrolysed wire and cable showed excellent electrical conductivity. With a conductivity of 98.2% IACS, these rods can be used in a number of industrial applications, especially in the electrical sector.

Its reduced environmental impact and economic viability make this process particularly suitable for small and medium-sized foundries. It offers a promising solution to the growing need for sustainable copper recycling, contributing to resource conservation and the circular economy.

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