ARCHIVES
of
FOUNDRY ENGINEERING
10.24425/afe.2026.158011
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences
ISSN (2299-2944)
Volume 2026
Issue 2/2026
228 – 237
28/2

High-Purity Copper Recovery from Fine Enameled Wires by Controlled Pyrolysis and Property Evaluation

M. Ez-zine *, I. Touaiher, O. Choukri, T. Saoudi
QSM Laboratory, Mohammadia School of Engineers, Mohammed V University in Rabat, Morocco
* Corresponding author: e-mail: mohsine_ezzine@um5.ac.ma

Received 03.12.2025; accepted in revised form 13.03.2026; available online 14.07.2026

Abstract

The recovery of high-purity copper from used fine enameled wires without loss of mass is a valuable solution for foundries. Although this waste is widely available on the market, it remains undervalued due to significant losses during processing. This study presents an effective thermal recycling method for fine enameled copper wires, designed to remove insulation while preserving the metal's metallurgical properties. Pyrolysis was performed between 450°C and 900°C with constant holding phases, followed by remelting in an induction furnace. Chemical, microstructural (SEM and optical), and electrical analyses identified an optimal temperature of 550°C with a holding time of 82 minutes, based on a well-defined thermal sequence. At this temperature, the enamel is completely decomposed, resulting in copper with 99.5% purity before melting and a recovery rate exceeding 99%. After melting, the 8 mm wire produced had a uniform microstructure and an average conductivity of 97.2% IACS, aligning with industrial standards for wire drawing (electrical applications). In contrast, direct melting of untreated wires caused inclusions, metal losses, and reduced conductivity. The proposed process, which is simple and cost-effective, offers an efficient way to recycle this type of waste and supports the circular economy.

Keywords: Heat treatment, Metallography, Copper recycling, Fine enameled wires, Electrical conductivity

1. Introduction

The recycling of small-diameter enameled copper wires is essential in a circular economy, where global demand for copper could increase by 140% by 2050 compared to 2010 [1]. In 2021, approximately 33% of this demand was fulfilled through recycling copper waste [2]. These copper wires, used in various equipment such as motors and transformers, are a valuable resource in waste electrical and electronic equipment (WEEE). This equipment contains about 2.1 billion kg of copper, with 1 billion kg coming from cables and printed circuit boards [3]. Therefore, enhancing resource efficiency in copper waste management and adopting innovative recycling processes should be priority goals for global policy efforts aimed at reducing reliance on primary copper in the future [4-7]. For example, in Europe, the economic value of copper could increase by 22.5% by 2030 due to growing demand and the importance of recycling [8-9]. Additionally, copper recycling would reduce CO_2 emissions by 70 to 85% compared to primary production, while also reducing the energy consumption associated with copper extraction and processing [10].

Enameled copper wires, which are effective at both insulating and conducting current, are the main copper material used in manufacturing windings essential to the electrical industry [11]. In addition to their high electrical conductivity, these wires are highly ductile and can be easily cold-formed [12]. They consist of a copper core with over 99.9% purity [13-14], covered with an enamel coating that serves as insulation, with its composition chosen based on the operating temperature [15-17]. Common insulation materials include polyamide-imide (PAI), polyetherimide (PEI), polyurethane (PUR), polyamide (PI), or polyether ether ketone (PEEK), which can be reinforced with mica flakes or inorganic materials [18,19]. Insulation thickness is categorized into three types, creating a specific ratio between the copper and total cross-section depending on the dimensions of the copper core [20].

Recycling used fine enameled wires is more complex than recycling ordinary cables because the paint film binds strongly to their metal parts, making removal particularly difficult. This complexity presents a major challenge for efficient copper recovery, prompting researchers to test various stripping techniques. Among these, chemical processes are notably effective: degrading polyester coatings with an aqueous NaOH solution is a common approach [21]. Additionally, methanolysis using methanol and dichloromethane can break down polymers like polyvinyl butyral and polyester [22].

Mechanical approaches also provide promising solutions, such as using rotating friction wheels to remove insulation from ultra-fine wires [23], or employing centrifuges combined with chromite sand to separate paint layers from copper [24]. Thermally, pyrolysis is a key method that breaks down enamels at high temperatures and releases copper [25,26]. Other thermal techniques, like high-frequency induction heating, are also used to precisely remove polyester coatings at specific temperatures [27,28].

Finally, innovative approaches, such as laser ablation can be used to remove enamel coatings, although further optimizations are needed to prevent substrate melting [29]. Additionally, techniques combining pyrolysis and ultrasound have proven to be more effective in enhancing copper recovery, offering promising prospects for recycling enameled wires [30]. Lastly, our study [31] acknowledges certain limitations, particularly in the processing of fine wires, which often constitute a large portion of the old raw materials supplied to foundries. Otherwise, these wires tend to degrade rapidly during pretreatment, posing challenges to maintaining material integrity.

A detailed reading of the results from the methods mentioned above reveals that they have been tested under well-defined conditions on certain types of enameled wires. The recovery rates of these methods range from 98% to 99.99%, with the highest value achieved by combining two methods: pyrolysis and ultrasonic treatment. Although recovery rates vary between 94.52% and 99.95%, pyrolysis remains a promising approach for recycling enameled wires. Additionally, it is important to note that, under controlled conditions, the pyrolysis of these wires, which are composed of approximately 98% copper and produced in very large quantities, allows the insulating layer to be decomposed in a controlled manner, with a limited and manageable release of gaseous by products. To reduce the 1.9% mass loss, this study will propose an industrial pyrolysis process that is cost-effective and accessible to small foundries, with minimal environmental impact. This process enables efficient recycling of fine enameled wires (diameter 0.05 mm) to recover pure copper without oxidation or excessive mass loss, resulting in a product suitable for use in the upcasting manufacturing process. The effects of various factors, such as pyrolysis temperature and holding time, on treatment efficiency have been examined in detail.

2. Methodology

2.1. Materials: Sample preparation

After receiving the waste, the first step in the treatment process is manual sorting. This step aims to separate and remove impurities like plastic, powder, iron, aluminum, and other materials. Sorting is crucial before thermal treatment because it improves waste preparation and prevents the combustion of unwanted materials, such as plastic, which could harm the environment and reduce pyrolysis efficiency. Thorough manual sorting enhances the treatment's effectiveness. Afterward, samples weighing 20 to 30 grams (fine enameled wires) are prepared and weighed before treatment (Figure 1).

Fig. 1. (A) Waste batch, (B) Samples prepared after sorting

The enameled copper wires in this study have a total diameter of 0.05 mm, with a high-purity copper conductor (>99.9%) coated in enamel. According to IEC 60317 and NEMA MW 1000 standards, the enamel thickness is 0.005 to 0.01 mm, resulting in an effective copper core diameter of about 0.035–0.04 mm. The copper conductor is produced by intensive cold drawing, resulting in an initially heavily work-hardened state with elongated grains. This initial structural condition explains the particular sensitivity of the wires to thermal treatments. When exposed to elevated temperatures, cold-worked copper may undergo microstructural evolution processes such as recovery, internal stress relaxation, and recrystallization depending on the temperature and exposure time, as widely reported in the literature for cold-worked copper conductors [32]. However, in the present study, no metallographic characterization of the copper core was performed. Therefore, these mechanisms are mentioned only as possible phenomena reported in previous studies and should not be interpreted as experimentally demonstrated in the investigated material.

2.2. Heat treatment

The samples are placed inside the furnace (GT-072F-20*20 electric oven, 6 kW, 220 V), as shown in Figure 2, and the door is carefully closed to ensure a complete seal and prevent oxygen from entering, which could cause copper oxidation.

Before starting the treatment, a nitrogen purge is performed by injecting gas at a flow rate of 10 L/min for 15 minutes to remove oxygen and establish an inert environment. The nitrogen injection pressure stays steady at 10 bars throughout the entire treatment cycle. Once the internal atmosphere is saturated with nitrogen, the electric heater is turned on.

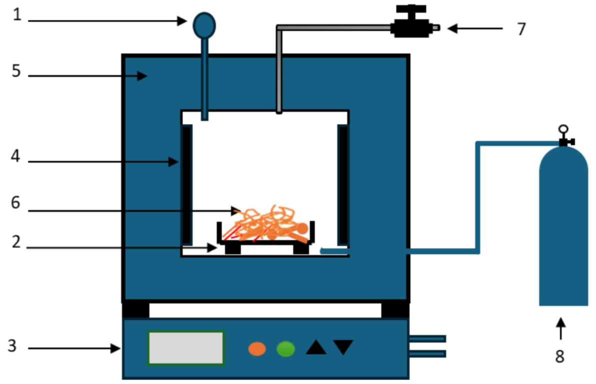

Fig. 2. Pyrolysis furnace: 1- thermocouple, 2- crucible, 3- regulator, 4- electrical resistance, 5- refractory insulation, 6- Enameled copper waste, 7- gas evacuation, 8- Inert gas

The furnace temperature gradually increases following the thermal profile (Figure 4) until reaching the desired temperature. Successive tests were conducted by increasing the temperature in steps of 50 °C (450 °C, 500 °C, 550 °C, 600 °C, 650 °C, 700 °C, 750 °C, 800 °C, 850 °C, and 900 °C) in order to investigate the behavior of the enamel coating and identify suitable pyrolysis conditions.

The selection of the temperature levels used in this study was guided by the thermal degradation behavior of polymeric enamel coatings commonly used in magnet wires. According to thermogravimetric and pyrolysis studies reported in the literature, the degradation of polyester-imide and related insulating resins occurs through several successive stages rather than through a single reaction. An initial stage between approximately 250 °C and 350 °C corresponds to the release of low-molecular-weight volatile compounds and the beginning of polymer decomposition. The main degradation of the insulation generally occurs between about 400 °C and 550 °C, where the polymer structure breaks down and most of the organic material is converted into gaseous products and carbonaceous residues. At higher temperatures, typically above 600 °C, the remaining carbonaceous residues and inorganic additives may undergo further decomposition or transformation depending on the thermal conditions [25,26,37–39]. Based on these mechanisms, the investigated temperature range (450–900 °C) was selected to cover both the principal enamel decomposition regime and the higher-temperature region where residual carbonaceous compounds may be further degraded. The step of 50 °C between successive experiments was adopted in order to progressively identify the temperature window allowing complete removal of the insulation while limiting thermal damage to the fine copper wires.

At each temperature sequence, a systematic protocol is followed after heat treatment. This involves separating the residues, washing, and then drying them in the open air, as shown in Figure 3.

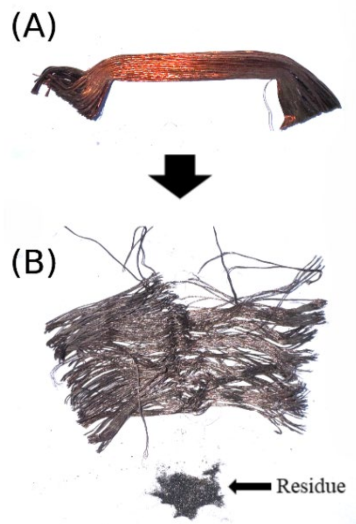

Fig. 3. (A) sample before treatment, (B) sample after treatment

The thermal profile used during treatment consists of four consecutive phases (Figure 4): The first phase is preheating to remove light volatile compounds without beginning to carbonize the insulation. The temperature gradually increases from room temperature to 300°C at a rate of 15°C/min, followed by a 10-minute stabilization period (holding stage) at this temperature. The second phase is devoted to the main decomposition of the insulating coating. The temperature is raised from 300°C to 450°C and maintained at 450°C for 15 minutes. The third phase aims to eliminate remaining solid residues. It involves raising the temperature from 450°C to a final value (which varies depending on the tests), then stabilizing at that level for 10 minutes. Finally, the fourth phase involves gradual cooling, carried out with the power off, while continuously injecting inert gas until the temperature drops to around 50°C.

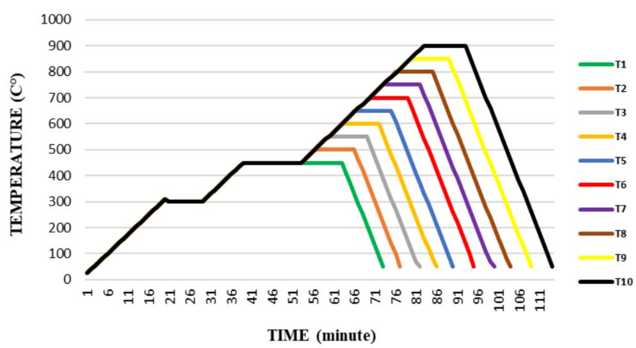

Fig. 4. Heat treatment profile

A multi-stage heat treatment was selected to control the progressive decomposition of the enamel layer while preserving the integrity of fine copper wires. This approach allows the different stages of enamel degradation to be separated, including the release of volatile compounds, the primary decomposition of the polymer matrix, and the elimination of residual carbonaceous products, while limiting excessive thermal exposure that could promote fragmentation or surface alteration of the cold-drawn copper wires. Single-step direct heating trials revealed clear limitations: at low temperatures, the enamel layer is not completely removed, whereas at high temperatures rapid carbonization of the insulation leads to wire embrittlement. Pyrolysis temperatures were therefore investigated through successive increments in the range of 450 to 900 °C in order to experimentally determine the processing window that allows effective insulation removal without excessive degradation of the copper. The corresponding holding times were defined based on the observed mass losses, the physical condition of the wires after treatment, and surface observations, while also taking into account previous studies on the thermal degradation of enamel coatings and the thermal pretreatment of recycled copper.

In order to identify the optimal processing conditions, the selection of the final thermal parameters was based on a comparative analysis of the experimental results obtained at each temperature level. The optimization criteria considered in this study included (i) the mass loss associated with enamel removal, (ii) the physical integrity of the fine copper wires after treatment, (iii) the surface condition of the wires, and (iv) the chemical purity and electrical conductivity of the recovered copper after remelting.

To evaluate these criteria, several parameters were systematically measured after each thermal treatment. Mass loss was determined by comparing the residual mass to the initial mass. The physical condition of the copper wires was examined to detect signs of degradation, such as fragmentation during manual handling.

The surface morphology of the wires was analyzed using scanning electron microscopy (SEM, Thermo Scientific Quattro S, Thermo Fisher Scientific). Observations were performed at an accelerating voltage of 15 kV with a working distance of approximately 10.2 mm, using a secondary electron detector (LVD mode). SEM analyses were carried out on selected surface regions of the treated wires after cooling to room temperature. Several representative areas were analyzed for each sample to ensure the reliability and representativeness of the results.

The chemical composition of the recovered copper was determined by spectrometric analysis. The elemental composition of the solid residues was analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-OES, Ultima 2, Jobin Yvon/Horiba). Prior to ICP analysis, the samples were digested using nitric acid under controlled laboratory conditions. Calibration was performed using certified reference standards to ensure analytical reliability (each sample was analyzed in triplicate**)**. In addition, the residues (homogenized samples) were analyzed using wavelength-dispersive X-ray fluorescence spectroscopy (WDXRF, PANalytical Axios, Malvern PANalytical) to identify and quantify the main impurities present.

2.3. Melting and casting

For a more precise evaluation of the purity, microstructure, and electrical performance of the recycled copper, a sample of this thoroughly treated and washed wire was remelted in a 15-kW induction furnace with a capacity of 1000 g. The molten metal, heated to 1120 °C in the presence of a protective flux (graphite powder), was cast into a cooled graphite mold with an 8 mm diameter using flame-assisted pouring, with oscillation to prevent porosity. The goal was to produce an 8 mm diameter wire, similar to that produced by the UPCast process (Figure 5).

For comparison, a melting was also performed using samples of non-heat-treated enameled wires. This operation allowed for a direct evaluation of the impact of pretreatment on the metallurgical purity, microstructural state, and electrical performance of the recovered copper.

For micrographic observation, the samples were embedded in a thermosetting resin to make handling easier. Grinding was done with water using silicon carbide abrasive paper with progressively finer grit sizes (200, 400, 600, 1200). The surface was then polished with diamond paste until a mirror-like finish was achieved. Chemical etching was carried out with a reagent based on $FeCl_3$, HCl, and ethanol, following ASTM E407, to reveal the microstructure. Observation was performed using a TEELEN-4XC metallographic optical microscope.

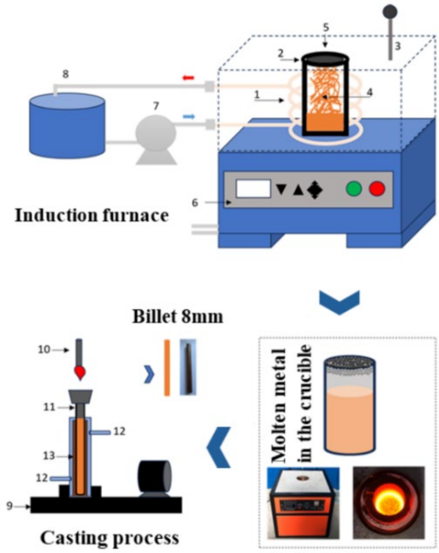

Fig. 5. Melting and Casting process: 1- Induction coil, 2- Graphite crucible, 3- Thermocouple, 4- Treated copper, 5- Protection flow, 6- Control panel, 7- Pump, 8- Cooling water, 9- Table of oscillation, 10- Flame, 11- Graphite mold 8mm, 12- Cooling water IN/OUT, 13- Cooper cooling jacket

Electrical conductivity was measured using a conductivity meter (SigmaScope SMP10) that was previously calibrated with certified standards for high-conductivity metals. The measurements were performed under strictly controlled conditions. To ensure good conductivity, the sample surfaces were cleaned with a diluted solution of sulfuric acid (H_2SO_4) or nitric acid (HNO_3), removing surface oxides effectively. The samples were then cut to lengths between 80 and 110 mm. Each sample was connected to a specific electrical circuit via electrodes delivering a current between 1 and 100 mA. The electrical resistance (R) was recorded, and the resistivity (ρ) was calculated from this value using equation (1), while the conductivity was determined using equation (2). The %IACS was then calculated using formula (3). Measurements were performed in an accredited laboratory using calibrated equipment, and the measurement uncertainty is estimated to be on the order of 1–2%.

$$\rho = R \times \left(\frac{A}{L}\right) \tag{1}$$

$$\sigma = \frac{1}{\rho} \tag{2}$$

$$\%\text{IACS} = \left(\frac{\sigma_{\text{measured}}}{\sigma_{\text{copper}}}\right) \times 100 \tag{3}$$

Where R is the measured resistance (in ohms), A is the cross-sectional area of the wire (in m2), and L is the length of the wire (in m).

3. Results and discussion

3.1. Mass loss results (after heat treatment)

For each sequence, the treatment was applied to three samples, and the average values obtained from these three measurements are summarized in Table 1:

Table 1.
Mass loss results as a function of processing temperature

Temperature (°C)	Initial mass (g)	Final mass (g)	Loss (g)	Loss (%)
T1 : 450°C	27.13	26.47	0.67	2.47%
T2 : 500°C	24.33	22.63	1.71	7.02%
T3 : 550°C	25.97	23.91	2.07	7.97%
T4 : 600°C	24.53	22.53	2.00	8.17%
T5 : 650°C	23.87	21.63	2.24	9.37%
T6 : 700°C	27.93	24.83	3.10	11.07%
T7 : 750°C	23.13	20.53	2.60	11.28%
T8 : 800°C	30.00	26.27	3.73	12.48%
T9 : 850°C	24.73	21.50	3.23	13.04%
T10 : 900°C	27.07	23.43	3.63	13.42%

Mass losses gradually increase with temperature, reaching an average of 13.42% at 900°C due to the decomposition of the enamel and the degradation and fragmentation of the wires, while remaining consistent among different samples at each stage. Regarding thermal effects, residue degradation becomes more noticeable above 450°C. The optimal temperature range is between 500 and 600°C, with a loss rate of 7 to 8%, which theoretically corresponds to the mass of the insulator.

The loss rate was confirmed by comparing it to the insulation ratio mandated by the standard [33,34]. The total diameter of the treated enameled wire is 0.05 mm, with an average enamel thickness per side ranging from 0.005 mm to 0.01 mm. This indicates that the actual diameter of the copper conductor lies between 0.03 mm and 0.04 mm, confirming the consistency between the measured mass loss and the theoretical amount of insulation (According to the calculation above).

-Volume of enameled wire:

$$\text{Vtotal} = \frac{\pi}{4}(\text{Dtotal})^2 = 0{,}00196\ \text{mm}^3$$

-Volume of copper:

$$\text{Vcopper} = \frac{\pi}{4}(\text{Dcopper})^2 = 0{,}00126\ \text{mm}^3$$

-Volume of enamel:

$$\text{Venamel} = \text{Vtotal} - \text{Vcopper} = 0{,}0007\ \text{mm}^3$$

-Proportion by weight of enamel:

$$\text{Taux enamel (\%)} = \frac{\text{Masse enamel}}{\text{Masse total}} \cdot 100 \approx 7{,}5\%$$

Where copper density = 8,96 g/cm³ and enamel density = 1,2 to 1,4 g/cm³.

Based on the calculations, an enameled wire with a diameter of 0.05 mm contains approximately 7 to 8% enamel by weight. This estimate corroborates the losses observed during heat treatment and confirms that a temperature of 550°C is optimal for ensuring effective removal of the insulation without excessive degradation of the copper.

At temperatures above 700 °C, noticeable surface degradation and physical fragmentation of the fine copper wires are observed, as shown in Figure 6. This behavior likely arises from a combination of effects. Although the treatment is performed under nitrogen purging, minor surface alteration may still occur due to traces of residual oxygen in the furnace or gas stream, especially at high temperatures and for very small wire diameters [35]. In addition, exposure to elevated temperatures can promote microstructural softening processes, such as recovery and possible recrystallization or grain growth, which may weaken the mechanical integrity of heavily cold-worked fine copper wires and favor fragmentation [36].

Fig. 6. Visual appearance of copper wires after heat treatment: (A) 550°C, (B) 700°C (qualitative observation of surface condition and fragmentation)

3.2. Chemical analysis results (after heat treatment)

At 550°C, analysis of the copper wire composition using a spectrometer (Table 2) shows a purity of 99.95%. The low concentrations of residual elements, especially lead (0.0007%) and zinc (0.002%), confirm the effective removal of the insulation and the retention of the wire's metallurgical properties. At this temperature, organic polymers decompose in the gas phase, while the continuous injection of inert gas minimizes the risk of copper oxidation [25].

Table 2.
Composition of copper wire after treatment

Element	%
Cu	99.95
Ag	≤ 0.002
Fe	≤ 0.01
Pb	0.0007
Zn	0.002
Ni	≤ 0.003
Sn	≤ 0.002
Sb	0.0008
As	≤ 0.005

3.3. SEM inspection results (after heat treatment)

To confirm the optimal temperature, SEM observations were conducted on samples treated between 500 and 650 °C. The changes in the surface morphology of the enameled copper wire as a result of heat treatment are shown in Figure 7.

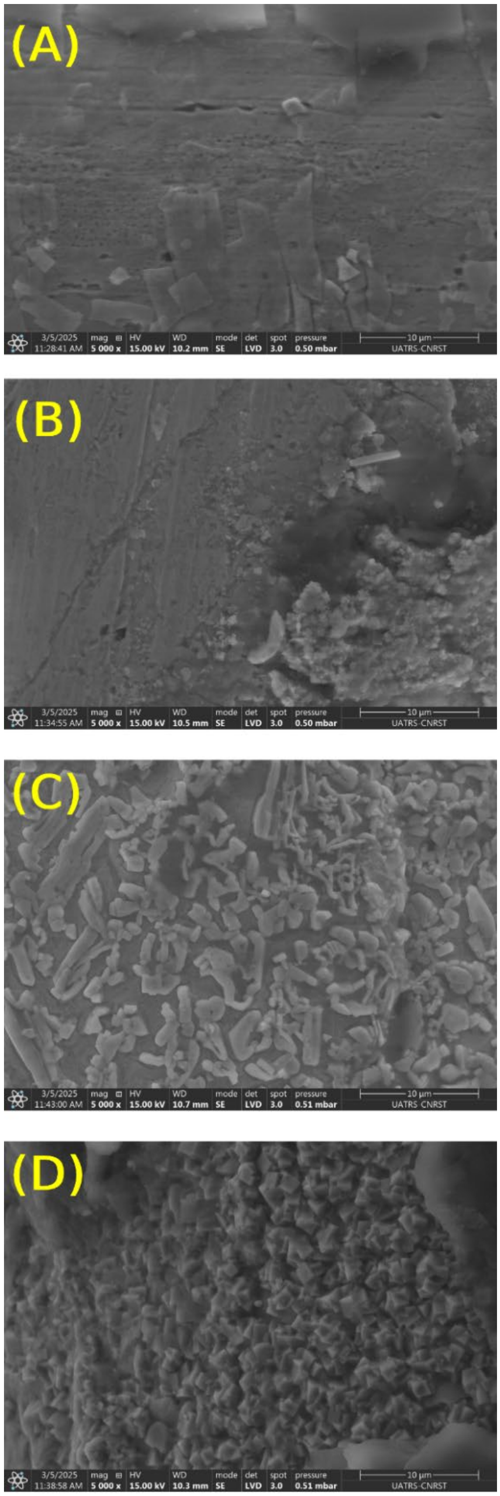

Fig. 7. SEM images and EDS results after heat treatment: (a) T=500C°, (b) T=550C°, (c) T=600C° and (d) T=650C°

The SEM images allow evaluation of the effect of heat treatment on the degradation and removal of the enamel coating. At 500 °C (Figure 7a), the cleaning of the surface remains incomplete, and residual material is still visible. At 550 °C (Figure 7b), the surface appears relatively uniform and cleaner compared with lower temperatures, indicating effective removal of the insulating layer. Above 550°C, the surface morphology progressively deteriorates. At 600 °C (Figure 7c), the surface becomes slightly rough and irregular. At 650 °C (Figure 7d), a significant increase in surface roughness is observed, suggesting thermal alteration of the copper surface. These observations indicate that excessive temperatures may lead to degradation of the copper surface. Overall, the SEM observations confirm that 550 °C represents the most suitable temperature for the thermal pretreatment of fine enameled copper wires, enabling effective removal of the insulating coating while preserving the surface integrity of the copper.

3.4. Residue analysis results (after heat treatment)

The results obtained (Table 3) show a clear evolution in the chemical composition of the residues between 550 and 900°C. These mainly contain carbon (~47–49%) as well as several inorganic oxides commonly found in insulating enamel formulations, notably SiO_2, Al_2O_3, CaO, MgO, TiO_2, P_2O_5, and K_2O. These compounds confirm that the residues mainly originate from the thermal decomposition of the enamel (particularly polyester-imides) [37,38,39]. The gradual increase in copper content in the residues, from 0.88% to 55.27%, is due to the gradual oxidation of the metal (formation of Cu_2O/CuO), as well as the physical disintegration of the wire caused by heat [35]. Simultaneously, certain volatile or semi-volatile elements, such as Cl, S, Pb, and Zn, decrease significantly, indicating their partial elimination as gases [40]. The presence of certain trace elements, such as antimony, tin, or nickel, may result either from fire-retardant additives incorporated into the insulation or from contamination originating from metallic or processing sources. These results highlight that, above 600°C, the residues no longer solely reflect the degradation of the enamel but also include the decomposition of the copper wire itself.
Table 3 values come from different techniques. XRF results are in wt.% for oxides and elements, ICP results in ppm for trace elements. These data are not a normalized mass balance; their sum isn't expected to be 100 wt.%.

3.5. Microstructural inspection results (after melting and casting)

Direct melting of enameled copper wires without prior heat treatment is unsuitable for producing high-quality pure copper. This is because the insulating enamels, made of resins and organic polymers (such as polyimides R−(CO)$_2$−R'), decompose and carbonize at high temperatures. These carbon residues can be incorporated into the metal bath, leading to the formation of internal defects or reacting with copper to form oxides (Cu_2O, CuO), which reduce purity [25]. This contamination is evident in micrograph (a) (Figure 8), where dark inclusions appear within the metal matrix. A high slag rate is observed, containing a significant amount of unrecovered copper, requiring complex and costly secondary treatments. Conversely, copper obtained after preliminary heat treatment at 550°C, shown in micrograph (b), features a more homogeneous structure with no visible defects, indicating clean melting and purified metal. These results highlight the importance of thermal pretreatment by pyrolysis before melting to prevent losses and ensure metallurgical quality suitable for electrical applications requirements.

Table 3.
Results of powder residue analysis by XRF (Wt. %) and ICP (ppm)

Element	E1 (550C°)	E2 (600C°)	E3 (700 C°)	E4 (800 C°)	E5 (900 C°)	Method
Al2O3	3.26	3.01	2.69	3.94	3.38	XRF
CaO	1.57	1.76	1.81	1.62	1.59	XRF
Fe2O3	1.72	1.97	1.82	1.81	1.75	XRF
K2O	0.65	0.97	1.12	1.21	0.88	XRF
MgO	0.38	0.41	0.55	0.83	0.76	XRF
P2O5	1.86	1.87	1.87	1.88	1.86	XRF
S	0.35	0.39	0.34	0.15	0.07	XRF
SiO2	11.19	10.87	10.9	8.97	7.48	XRF
TiO2	1.01	0.97	0.89	0.52	0.58	XRF
Cl	0.73	0.54	0.27	0.24	0.24	XRF
Cu	0.88	3.33	25.3	49.8	55.3	XRF
Pb	0.61	0.56	0.35	0.31	0.16	XRF
Zn	0.31	0.26	0.28	0.24	0.18	XRF
C	48.97	46.87	49.0	48.1	47.6	XRF
As	<7	<7	<7	<8	<8	ICP
Cd	1	<1	<1	<1	<1	ICP
Co	1	<3	<2	<5	<5	ICP
Li	<3	<3	<3	<3	<3	ICP
Mo	<10	<11	<10	<10	< 10	ICP
Ni	13	17	11	23	15	ICP
Sb	28	29	34	35	27	ICP
Sn	87	83	91	86	77	ICP
Sr	5	5	5	5	5	ICP
Y	3	3	3	3	3	ICP

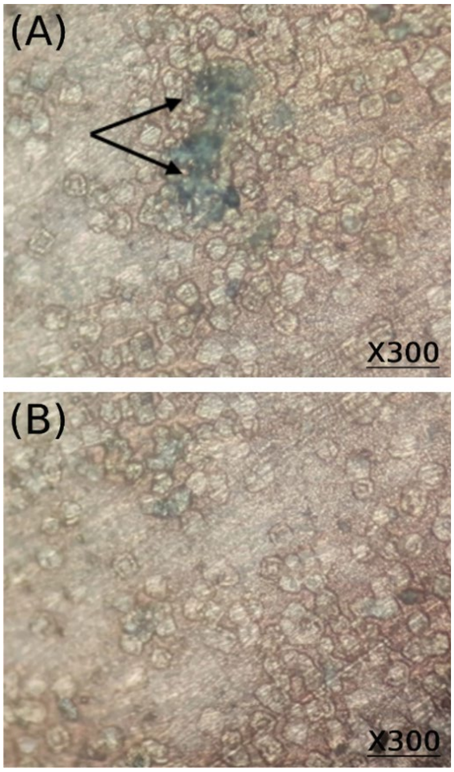

Fig. 8. Micrographic structure of the 8mm wire: (A) untreated, (B) after treatment at 550°C

Although the remelted copper after pyrolysis appears generally homogeneous, small isolated features may occasionally be observed, likely corresponding to minor oxide inclusions or residual impurity phases typical of recycled copper.

3.6. Electrical conductivity measurement results (after melting and casting)

After heat treatment at 550°C through pyrolysis, the wires were washed and remelted to homogenize the copper and remove volatile or non-metallic impurities. This process produced a denser and purer 8 mm copper wire. The measured average electrical conductivity is approximately 56.87×10^6 $S \cdot m^{-1}$, reflecting the intrinsic quality of the recovered copper. The IACS (International Annealed Copper Standard) value exceeds 97% (Table 5), with copper purity reaching 99.95% (Cu-a1), which meets the requirements for copper wire intended for drawing in electrical applications [41]. However, it is important to note that even after treatment, traces of residual impurities (including stable oxides, carbon, or trace elements such as sulfur and lead) may remain in the matrix. These elements, known to increase the resistivity of copper, explain the slight difference observed from the theoretical value of 100% IACS.

In contrast, the conductivity of the 8 mm copper wire made from directly melting untreated wires averaged only 54.5×10^6 $S \cdot m^{-1}$ (Table 4). This reduction in performance is due to the residual presence of carbon, oxides, or other impurities from the varnish, which can increase the electrical resistance of the material and therefore decrease its conductivity [42].

Table 1.
Result of the electrical conductivity measurement of the 8 mm copper wire obtained from untreated samples

Sample	Conductivity (S.m-1)	ICAS (%)
S1	55508917,2	94,88704
S2	53073396,9	90,72376
S3	54917735,4	93,87647
Average	54500016,5	93,16242

Table 2.
Result of the electrical conductivity measurement of the 8 mm copper wire obtained from samples treated at 550°C

Sample	Conductivity (S.m-1)	ICAS (%)
S1	57224378,6	97,81945
S2	56724100,7	96,96427
S3	56619949,4	96,78624
Average	56856142,9	97,18999

4. Conclusions

This study has demonstrated an effective and sustainable method for recycling copper from fine enameled wires. Controlled heat treatment in an electric pyrolysis furnace, following an optimized profile (550°C for 82 minutes), efficiently removes the insulation without changing the metal's shape or losing mass. Analytical results show copper recovery of over 99%, with purity above 99.9% before melting. After remelting, the 8 mm wire produced has a uniform microstructure, no visible defects, and an average electrical conductivity of over 97% IACS, meeting the requirements for wire drawing in electrical applications. In contrast, direct melting without thermal pretreatment causes high fire losses, metallurgical defects, and a notable drop in electrical conductivity. This process, which is simple to implement and accessible to small foundries, offers a promising solution for effectively recycling fine enameled copper wire waste, while helping reduce metal losses and promoting the circular economy.

References

[1] Born, K. & Ciftci, M.M. (2024). The limitations of end-of-life copper recycling and its implications for the circular economy of metals. *Resources, Conservation and Recycling.* 200, 107318, 1-10. DOI: 10.1016/j.resconrec.2023.107318.
[2] International Copper Study Group (2022). *The World Copper Factbook 2022*. Lisbon: ICSG.
[3] United Nations Institute for Training and Research (2024). *Global E-Waste Monitor*. UNITAR, Geneva (2024).

[4] Klose, S. & Pauliuk, S. (2021). Quantifying longevity and circularity of copper for different resource efficiency policies at the material and product levels. *Journal of Industrial Ecology*. 25, 979-993. DOI: 10.1111/jiec.13092.

[5] Cocquerel, M.A.T. & Burcher, M.G. (1978). Aspects of recycling copper scrap. *Conservation & Recycling.* 2(2), 111-116. DOI: 10.1016/0361-3658(78)90049-8

[6] Gomez, F., Guzman, J.I. & Tilton, J.E. (2007). Copper recycling and scrap availability. *Resources Policy*. 32(4), 183-190. DOI: 10.1016/j.resourpol.2007.08.002.

[7] Yu, H., Sun, H., Liu, W., Zhang, R., Yan, Y. & Wu, S. (2021). A multidimensional evaluation method for the service life of scrapped copper wires. *Advanced Sustainable Systems*. 5(10), 2100160, 1-12. https://doi.org/10.1002/adsu.202100160.

[8] European Copper Institute (2023). *Waste from Electrical and Electronic Equipment (WEEE)*. Brussels: ECI.

[9] Gnatush, V. (2024). Global market trends for secondary processing of copper waste and scrap. *Metallurgy and Casting of Ukraine.* 3-12. DOI:10.15407/steelcast2024.01.006.

[10] European Recycling Industries' Confederation (2020). *Metal Recycling Factsheet*. Brussels: EuRIC.

[11] Hagedorn, J., Sell-Le Blanc, F., Fleischer, J. (2017). *Handbook of coil winding: technologies for efficient electrical wound products and their automated production*. Berlin–Heidelberg: Springer Vieweg,.

[12] Deutsches Kupfer-Institut e.V. (2000). *Kupfer in der elektrotechnik - kabel und leitungen.* Deutsches Kupfer-Institut, Düsseldorf.

[13] Deutsches Kupfer-Institut. (2019). *Cu-ETP (Electrolytic Tough Pitch Copper) – Material Data Sheet*. Deutsches Kupfer-Institut, Düsseldorf.

[14] Elektrisola GmbH. (2024). *Enamelled Wire*. Technical Brochure. Reichshof, Germany.

[15] Heib, B. (2017). *Développement de vernis d'isolation électrique présentant des propriétés thermomécaniques améliorées à 180 °C.* PhD Thesis, Université de Lorraine, Nancy.

[16] Hoang, A.T., Serdyuk, Y.V. &, Gubanski, S.M. (2014). Electrical characterization of a new enamel insulation. *IEEE Transactions on Dielectrics and Electrical Insulation*. 21(3), 1291-1301. DOI: 10.1109/TDEI.2014.004494.

[17] Winkeler, M. (1991). Magnet wire enamels – which one? *IEEE Electrical Insulation Magazine*. 794, 61-64. DOI: 10.1109/57.87662.

[18] Uchechukwu, A. M., Anthony, E. & Godspower, E. (2019). Electrical properties of enamel wire insulation. *International Journal of Trend in Scientific Research and Development*. 3(2), 803-806.

[19] Murray, T.J. (2008). Poly(amide-imides): wire enamels with excellent thermal and chemical properties. *Macromolecular Materials and Engineering*. 293(5), 350-360. DOI: 10.1002/mame.200700365.

[20] Mayr, A., Baader, M., Raffin, T., Riedel, A. & Franke, J. (2022). Towards an intelligent straightening system for flat enameled copper wire: problem statement, review of related work, and basic concept. *Procedia CIRP.* 115, 220-225. DOI: 10.1016/j.procir.2022.10.077.

[21] He, J. & Shan, G.-R. (2016). Controlled degradation and removal of polyester coatings on polyester enamelled wire, *Transactions of Materials and Heat Treatment.* 30(6), 1353-1358. DOI: 10.3969/j.issn.1003-9015.2016.06.017.

[22] Widijatmoko, S., Li, Y., Leeke, G. (2024). Enameled Copper Wire Recycling: Current Research Landscape and a Case Study for Enamel Removal. In: Proceedings of the 5th International Conference on Waste Recycling and Management (ICWRM 2024), Tokyo, Japan.

[23] Walker, I.R. (2004). Removal of enamel from ultrafine monofilamentary wires. *Review of Scientific Instruments.* 75(5), 1169-1174. DOI: 10.1063/1.1666992.

[24] Hu, B., Yuan, K. (2018). Study on removal of copper rice paint film and copper recovery efficiency. *IOP Conference Series: Materials Science and Engineering.* 452(2), 022062, 1-5. DOI: 10.1088/1757-899X/452/2/022062.

[25] Liu, W., Wang, N., Han, J., Xu, J., Li, Z. & Qin, W. (2020). Thermal degradation behaviors and evolved products analysis of polyester paint and waste enameled wires during pyrolysis. *Waste Management.* 107, 82-90. DOI: 10.1016/j.wasman.2020.04.005.

[26] Li, B., Wang, X., Xia, Z., Zhou, W., Wu, Y. & Zhu, G. (2023). Co-pyrolysis of waste polyester enameled wires and polyvinyl chloride: evolved products and pyrolysis mechanism analysis. *Journal of Analytical and Applied Pyrolysis.* 169, 105816. DOI: 10.1016/j.jaap.2022.105816.

[27] Song, O., Kim, J., Park, J., Kong, M. & Lee, C.S. (2012). Separation of enamel from the enamel-coated copper wires via high-frequency induction process. *Journal of the Korean Institute of Resources Recycling*. 21(3), 48-55. DOI: 10.7844/kirr.2012.21.3.048.

[28] Haque, M.M., Kim, H., Kong, M.-S., Hong, H.-S., Kim, K.S. & Lee, C.S. (2012). Recycling copper from waste copper wire using an applied voltage. *International Journal of Precision Engineering and Manufacturing*. 13(7), 1251-1257. DOI: 10.1007/s12541-012-0167-3.

[29] Madhukar, Y.K., Mullick, S., Shuklam D.K., Kumarm S. & Nath, A.K. (2013). Effect of laser operating mode in paint removal with a fiber laser. *Applied Surface Science.* 264, 892-901. DOI: 10.1016/j.apsusc.2012.10.193.

[30] Ma, S., Xing, P., Li, H., Wang, C., Hou, X., Cun, Z., Liu, M. & Yan, R. (2023). Recovery of high-grade copper from waste polyester imide enamelled wires by pyrolysis and ultrasonic treatment. *Resources, Conservation and Recycling.* 196, 107034, 1-9. DOI: 10.1016/j.resconrec.2023.107034.

[31] Ez-zine, M., Choukri, O. & Taibi, S. (2025). Impact of thermal pretreatment process on recycled copper purity. *Tribology and Materials.* 4(3), 155-164.

[32] Humphreys, F.J., Hatherly, M. (2004). *Recrystallization and related annealing phenomena*. 2nd ed. Oxford: Elsevier.

[33] International Electrotechnical Commission. (2015). *IEC 60317: Specifications for particular types of winding wires – Part X: Enameled round copper wire*. Geneva: IEC.

[34] National Electrical Manufacturers Association (NEMA). (2020). *ANSI/NEMA MW 1000-2020: Magnet Wire*. Rosslyn, VA, USA.

[35] Choukri, O., Ez-zine, M. & Taibi, S. (2024). Industrial recycling of scrap copper cables and wires: combining cold and hot treatments for maximum recovery and minimal emissions. *Archives of Foundry Engineering*. 24(4), 153-162. DOI: 10.24425/afe.2024.151323.

[36] Humphreys, F.J., Hatherly, M. (2004). *Recrystallization and Related Annealing Phenomena*. 2nd ed. Oxford: Elsevier.
[37] Chaala, A., Darmstadt, H. & Roy, C. (1997). Vacuum pyrolysis of electric cable wastes. *Journal of Analytical and Applied Pyrolysis.* 39(1), 79-96. DOI: 10.1016/S0165-2370(96)00964-3.
[38] Araki, C., Taguchi, T. (1993). Thermal degradation of polyesterimide magnet wire. In: Proceedings of the IEEE Conference on Electrical Insulation and Dielectric Phenomena. Pocono Manor, PA 781-785. DOI: 10.1109/CEIDP.1993.378919.
[39] Cuevas, A.B., Leiva-Candia, D.E. & Dorado, M.P. (2024). An overview of pyrolysis as a waste treatment to produce eco-energy. *Energies.* 17(12), 2852, 1-32. DOI: 10.3390/en17122852.
[40] Lu-shi, S., Abanades, S., Lu, J.D., Flamant, G. & Gauthier, D. (2004). Volatilization of heavy metals during incineration of municipal solid wastes. *Journal of Environmental Sciences*. 16, 635-639.
[41] ASTM International. (2020). ASTM B49-20: Standard Specification for Copper Rod for Electrical Purposes, ASTM, West Conshohocken, PA.
[42] Sadzikowski, M., Kiesiewicz, G., Noga, P., Franczak, K., Kwaśniewski, P., Ścieżor, W. & Kordaszewski, S. (2025). Effect of impurities on the properties of 'Cu ETP' copper produced from railway scrap. *International Journal of Advanced Manufacturing Technology.* 138(11), 5215-5227. DOI: 10.1007/s00170-025-15790-7.