Tribology and Materials
Vol. 4, No. 3, 2025, pp. 155-164

ISSN 2812-9717
https://doi.org/10.46793/tribomat.2025.012

Impact of thermal pretreatment process on recycled copper purity

Mohsine EZ-ZINE *, **Omar CHOUKRI**, **Souadi TAIBI**

Mohammadia School of Engineers, Mohammed V University, Rabat, Morocco
*Corresponding author: mohsine_ezzine@um5.ac.ma

Keywords
thermal pretreatment
purity
isothermal holds
holding times
mass losses

History
Received: 05-06-2025
Revised: 23-07-2025
Accepted: 04-08-2025

Abstract

Recent research has focused on improving the copper refining process to meet the stringent purity standards required by industries such as aerospace. This research builds on our previous study, which identified 1120 °C as the minimum melting temperature required to achieve optimum copper purity from recycled copper scrap. In this phase, we are investigating the effects of thermal pretreatment of copper scrap samples at specific temperatures prior to melting and casting at 1120 °C. The initial thermal pretreatment process involved continuous heating with isothermal holds at six target temperatures (200, 300, 500, 700, 850 and 950 °C). For each test, the duration of the isothermal hold at each temperature was fixed at 5, 10, 15 or 20 minutes, depending on the selected refining sequence. This method significantly improved the purity of the cast copper, increasing it from 99.9230 to 99.9714 wt. %. However, significant mass losses were noticed when holding times exceeded 10 minutes, mainly due to the thermal degradation and fragmentation of thin copper wires. To overcome this, alternative thermal pretreatment techniques were investigated using different holding times. One of the most effective refinements, consisting of a holding time sequence of 5–5–10–10–15–5 minutes at selected isothermal stages, increased the purity to 99.9716 wt. % and achieved a thermal conductivity of approximately 362 W/mK, while reducing the total refining time to 94 minutes. These findings help to optimise the copper refining process by reducing both costs and mass losses while improving overall efficiency.

1. Introduction

The need for effective resource management has become more crucial, especially with the rise of the circular economy, which encourages more careful use of materials. This approach emphasises material reuse and recycling to reduce waste and preserve our valuable natural resources [1,2]. The example of this approach is copper recycling through processes such as mechanical separation and fire refining, a metal widely used in numerous industries like electrical engineering, electronics, construction and transportation. Despite significant growth in copper consumption and primary production in recent years, secondary production has remained stagnant [3]. This situation is particularly notable given that the average service life of copper in use ranges between 10 and 30 years, meaning that the copper reaching the end of its life today was likely produced at the turn of the millennium [3]. This stagnation highlights the challenge facing the copper industry in integrating more sustainable practices while considering issues related to energy efficiency, greenhouse gas emissions reduction and climate change mitigation.

Recycled scrap used to produce secondary copper can be sourced from old metal scrap and end-of-life products, as well as new scrap generated during the production of copper-containing goods [4]. New industrial scrap is generally less expensive to recycle, as it is clean, homogeneous and requires minimal sorting or

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) license

pretreatment. However, old stored scrap that has accumulated in increasing quantities over time must be identified and separated by direct [5] or indirect [6] methods before recycling. Generally, waste is processed to remove high-melting point impurities such as ceramics, which would otherwise increase energy consumption during recycling. Companies that only have melting furnaces without refining equipment are limited to using high-purity waste materials such as industrial waste (usually provided by their customers) and ISRI (Institute of Scrap Recycling Industries) grade *Barley*/*Berry*/*Candy* copper (clean looking, unalloyed, uncoated, typically with copper content ≥ 98 wt. %). In contrast, those that incorporate a refining step into their process can also handle enamelled and wound wires, transformer windings, cut radiators and ISRI grade *Birch*/*Cliff* copper (mixed copper scrap with typical copper content ranging from 94 to 96 wt. %). As for foundries, they accept a wide variety of materials, even those containing low quantities of copper [7].

Most of the research in copper purification has utilised melting, cutting or mixing scrap copper with Cu_2S [8]. In addition, various types of copper-containing materials have been investigated in separate studies, including polymer-coated wires [9], electrolytic copper plates [10], blister copper [11], copper bars [12], copper concentrates [13], anode slimes from electrolysis [14] and electronic waste [15]. By conducting experiments under specific conditions, such as in a vacuum (with or without expansion) or using chemical agents, these studies have achieved the production of 5N copper (99.999 wt. %) through pyrometallurgy and 6N copper (99.9999 wt. %) through hydrometallurgy. In theory, thermal refining exploits the volatilisation of certain impurities, whose pressures are higher than that of copper, thereby improving the purity of the cast copper [16].

In recent years, China has reduced its imports of both low-quality copper scrap (Category 7) and higher-quality copper scrap (Category 6) as part of its "green" policy [17]. This decline has spurred the growth of the copper recycling industry in many countries, including Morocco, which exports over 19,000 tons of copper scrap annually [18]. To enable this industry to produce copper with a purity close to 4N (99.99 wt. %), which is widely used across various industrial sectors [19], this paper investigates a thermal pretreatment process applied to copper scrap in an industrial setting. The aim is to produce semi-finished copper with the highest possible purity and reduce copper losses associated with wire degradation. This process, involving melting the scrap at 1120 °C [20], has demonstrated a significant reduction in impurity levels and resulted in higher purity compared to previous studies.

2. Materials and methods

The experiments were conducted at the Benomar Metal Company foundry in Morocco. Samples, averaging 498 g (Fig. 1), were selected from the dirtiest copper scraps regularly processed into semi-finished products at this foundry. These samples mainly included winding wires, radiator tubes, various electrical wires, copper plates and ingots, copper scraps, pipework, connecting elements, and parts from appliances and automobiles.

The used raw materials were cleaned with water in a rotary drum to remove surface impurities, especially soil. Thermal pretreatment was carried out in a Gold Tool GT-072F electric furnace, which has a power capacity of 3 kW. This furnace is equipped with a regulator that maintains the required temperatures for the selected periods. All melting was conducted at 1120 °C in a Shanghai Fortune Electric induction furnace JD-25 using a high-density graphite crucible that meets

Figure 1. Samples of raw material used

the specifications of the SIGRAFINE® R7510 grade. This temperature is identified as the optimal melting-casting temperature for copper scrap, resulting in higher copper purity [20].

After melting, the samples were cast as copper billets using a graphite mould with an internal diameter of 26 mm and a length of 100 mm (Fig. 2). These billets were surfaced and polished before being analysed with a SPECTROMAXx optical emission spectrometer to determine their chemical composition using a certified standard, resulting in a standard deviation of 2 %. It should be noted that the chemical composition represents the average of more than four measurements distributed across the entire surface of each billet, especially at the middle and both ends.

Figure 2. Copper billet cast at 1120 °C

First, a sample that had not undergone thermal pretreatment was melted at 1120 °C and cast to determine its approximate chemical composition. Spectrometric analysis of this casting revealed a copper content of 99.92 wt. %. For each selected period (5, 10, 15 and 20 minutes), three tests were conducted. In each test, the sample was heated from ambient temperature up to 950 °C through successive isothermal holding stages at 200, 300, 500, 700, 850 and 950 °C [21,22]. At each of these six temperatures, the sample was held isothermally for the same duration as the selected period. For example, for the 10-minute test, the sample was maintained for 10 minutes at each stage (i.e. at 200 °C for 10 min, at 300 °C for 10 min, etc.). Thus, total pretreatment durations (holding and heating time) were 72, 102, 140 and 163 minutes, respectively, for the 5, 10, 15 and 20-minute tests. The duration of each holding stage was equal to the selected period (Fig. 3). After cooling in air, the sample was melted and cast into a graphite mould. The melting process was carried out without using any protective flux (i.e. a solid material placed over the melting bath to limit oxidation).

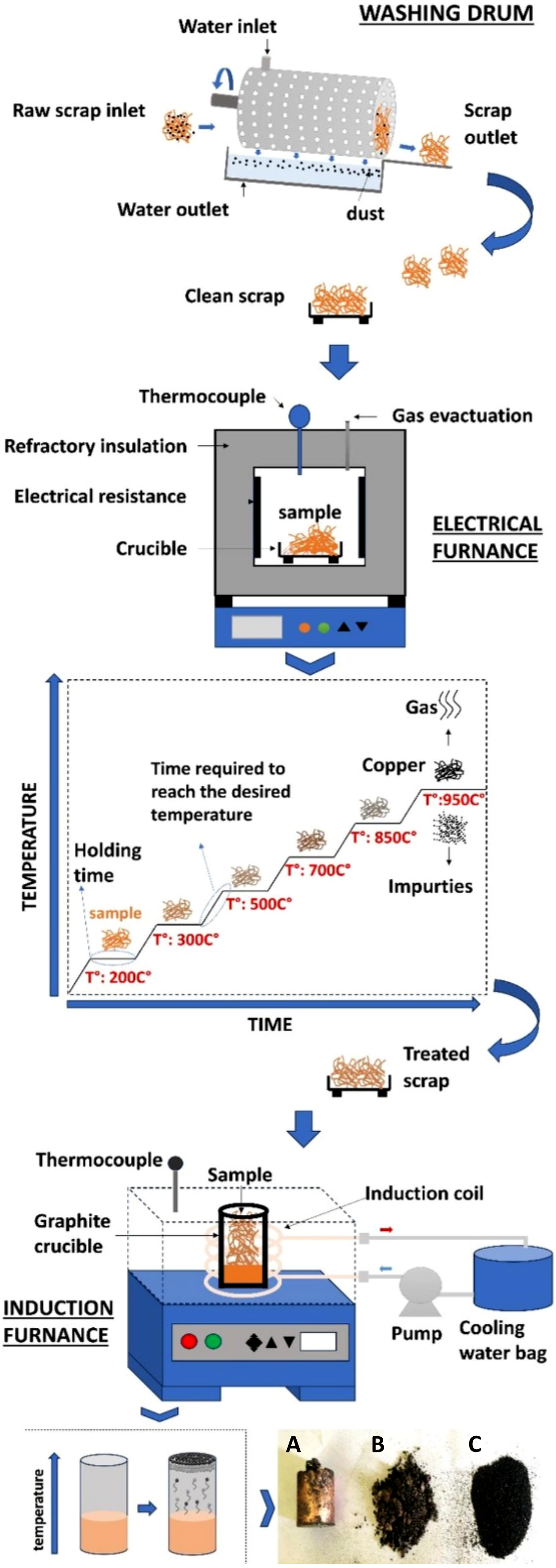

Figure 3. Thermal pretreatment, melting and casting process: A – copper billet, B – slag and C – residues

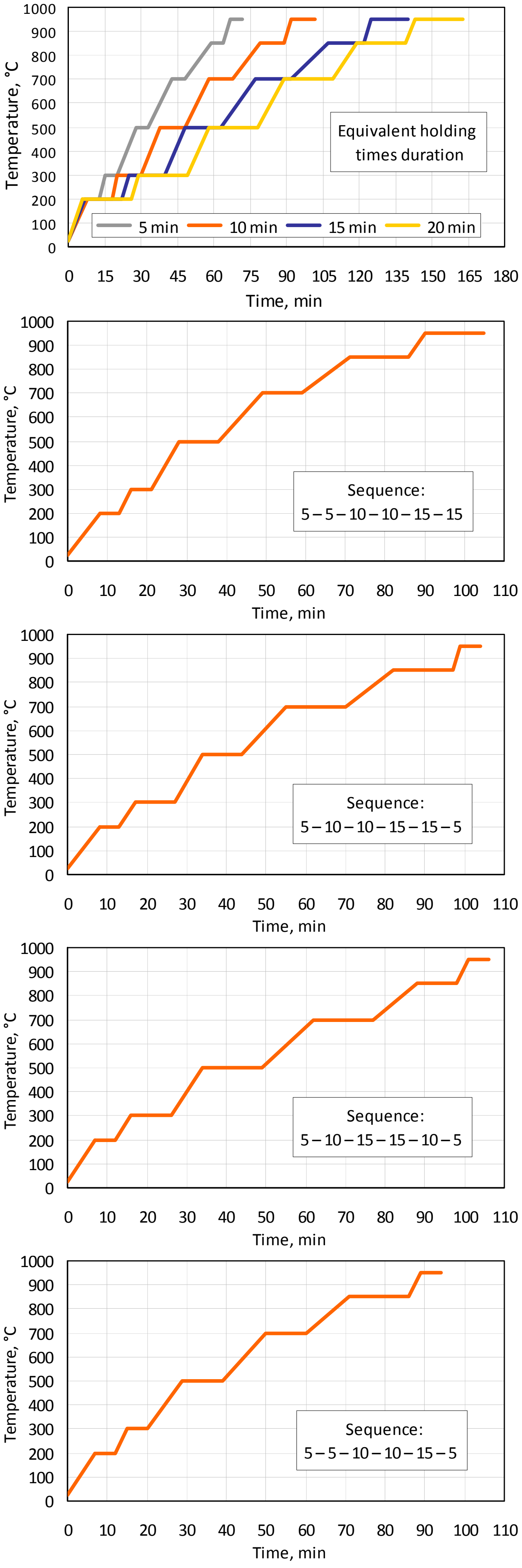

Figure 4. Thermal pretreatment sequences

A second set of experiments was conducted using more advanced holding sequences in addition to the standard thermal protocol with equal holding durations. The goal of these variable time sequences is to optimise purity while reducing copper losses. Figure 4 illustrates the various thermal pretreatment sequences used.

To evaluate the efficiency and effectiveness of the process, X-ray fluorescence (XRF) analysis was performed specifically on the residues and slag produced. This technique allowed for the precise determination of their chemical compositions.

The average thermal conductivity of the sample was determined using the same approach outlined in our previous study [20]. Initially, the billet was cut into a disc with a diameter of 2.5 cm and a thickness of 3.34 mm. The thermal conductivity determination process utilises the PA Hilton linear heat conduction unit H112A. Configured as a vertical column, this unit is equipped with eight thermocouples spaced 15 mm apart, into which the sample disc is inserted. The disc is inserted between the thermocouples to ensure proper thermal contact and accurate temperature gradient measurements. The variation in voltage applied to the H112A unit enables the adjustment of the heat flux within the column.

The average thermal conductivity K was determined using the following equation, provided in the user manual of the H112A linear heat conduction unit:

$$K = \frac{U I \Delta X}{A \Delta T}, \tag{1}$$

where U is the voltage applied to the heater in V, I is the electric current through the heater in A, ΔX is the sample thickness in m increased by 0.015 m, A is the cross-sectional area of the sample perpendicular to the heat flow direction in m^2 and ΔT is the temperature difference across the sample in K ($\Delta T = T_{hot} - T_{cold}$), T_{hot} is the temperature on the hot side of the sample in K, T_{cold} is the temperature on the cold side of the sample in K.

To determine the electrical conductivity, the billet was machined into a 10 × 10 × 1 mm square. It was then mounted on the spring clip board of the Ecopia Hall effect measurement system HMS-5300, which enables contact through spring-loaded clips and tips without requiring wire bonding (Fig. 5). Four measurements were conducted under consistent conditions and the electrical conductivity was determined by averaging these values.

Figure 5. Square (left) and spring clip board (right)

Electrical conductivity was also theoretically estimated using the Wiedemann-Franz law:

$$\sigma = \frac{K}{L_0 T}, \tag{2}$$

where σ is the electrical conductivity in S/m, K is the measured thermal conductivity in W/mK, L_0 is the Lorenz number (approximately equal to 2.44×10^{-8} WΩ/K^2) and T is the absolute temperature in K.

3. Results and discussion

The thermal mapping analysis of impurity elements in copper reveals that fifteen of these elements (Mo, Th, Nb, Zr, U, B, V, sTi, Gd, Be, Co, Ge, Cr, Fe and Ni) have boiling points higher than that of copper, while the remaining sixteen elements (Au, Ga, Si, Al, Sn, Ag, Mn, Pb, Sb, Bi, Ca, Te, Li, Mg, Zn and Na) have lower boiling points [23]. This observation will be used in the thermal pretreatment process described in this study to reduce the levels of certain impurities (P, Sn, Pb, Zn, Sb, Al and As) whose melting temperatures are below the maximum temperature of 950 °C. From a thermodynamic perspective, some of these impurities will volatilise during this process [24].

Under ambient conditions, only the Zn, P and As impurities present in the selected samples will exhibit high vapour pressures during thermal pretreatment [25]. Given that these elements constitute approximately 60 % of the total impurities in the untreated cast billet (Table 1), their reduction will significantly enhance copper purification. This process also facilitates the removal of enamel from the copper wire. The billet analysed in Table 1 was obtained by melting untreated copper scrap, using the casting conditions detailed in the previous section.

3.1 Preliminary results

According to Table 2, the mean copper content of billets obtained by melting treated samples ranges from 99.9692 to 99.9714 wt. %. This indicates an increase of approximately 0.05 % compared to billets derived from untreated samples. Conversely, the total impurity levels in the treated samples decreased significantly by 63 to 81 % compared to the untreated sample. This decline is mainly due to the decrease in the concentrations of volatile impurities such as Zn and P, whose sums decrease by approximately 0.69 to 0.93 % relative to the value noticed in the untreated sample, as shown in Figure 6. All results shown in Table 2 correspond to tests in which each isothermal holding stage (200, 300, 500, 700, 850 and 950 °C) was maintained for an equal duration of 5, 10, 15 or 20 minutes, as specified in the experiment.

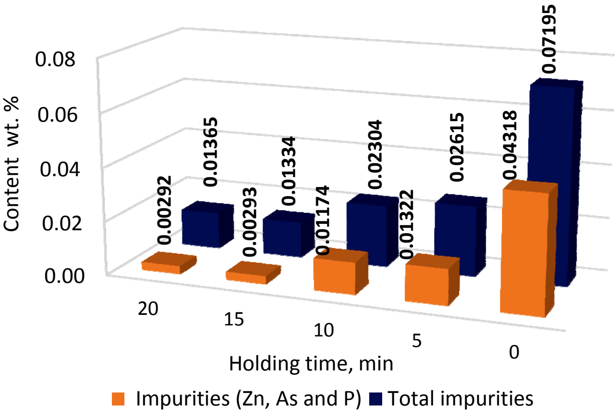

Figure 6. Effect of holding time on impurity reduction in copper billets under equal-duration thermal pretreatment stages

Table 1. Chemical composition of the billet cast from the untreated sample

Element	Zn	Pb	Sn	Ni	As	Sb	Ag	P	Fe	Si	Al	Be	Cu
wt. %	0.04141	0.0003	0.00291	0.0029	0.0002	0.00121	0.0003	0.00157	0.00282	0.0005	0.01769	0.0001	99.923

Table 2. Copper and impurity content in the billets cast from treated samples

Holding time, min	Element, wt. %												
	Zn	Pb	Sn	Ni	As	Sb	Ag	P	Fe	Si	Al	Be	Cu
20	0.00160	0.0003	0.00106	0.00290	0.0002	0.00114	0.0003	0.00112	0.00298	0.0005	0.00145	0.0001	99.9706
15	0.00162	0.0003	0.00094	0.00276	0.0002	0.00112	0.0003	0.00111	0.00305	0.0005	0.00134	0.0001	99.9714
10	0.01028	0.0003	0.00103	0.00323	0.0002	0.00170	0.0003	0.00126	0.00297	0.0005	0.00117	0.0001	99.9710
5	0.01187	0.0003	0.00214	0.00303	0.0002	0.00232	0.0003	0.00115	0.00291	0.0005	0.00133	0.0001	99.9692

It should be noted that the mass losses observed during the thermal pretreatment vary from 1.6 to 2.07 %. At the end of the billet casting process, these losses range from 5.7 to 6.21 % (Fig. 7).

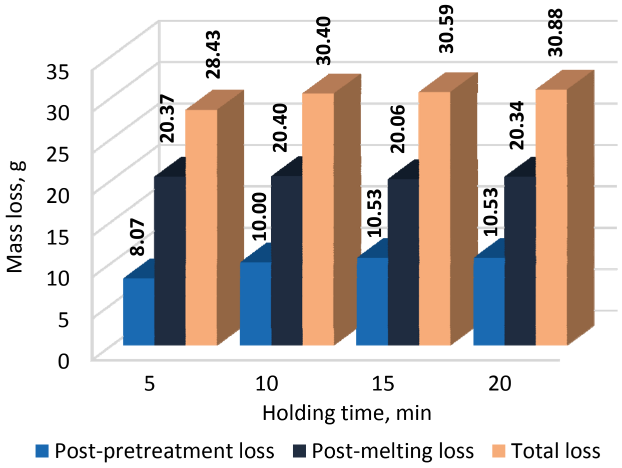

Figure 7. Variation of mass loss with holding time under equal-duration thermal pretreatment stages

The *mass loss* in % was calculated using the following formula:

$$mass\,loss = \frac{m_{\text{initial}}}{m_{\text{final}}}100, \tag{3}$$

where, for post-pretreatment, m_{initial} is the mass of the copper scrap sample before treatment in g, and m_{final} is the mass after pretreatment in g, and for post-melting, m_{initial} is the mass of the treated copper scrap in g and m_{final} is the mass of the billet after casting in g.

3.2 Analysis of residues and slag

The results obtained from XRF analysis (Table 3) of the residues and slag of the treated samples clearly show that the longer the thermal pretreatment time, the more the concentration of copper in the residue increases (Fig. 8). Conversely, this concentration decreases in the slag. This relationship between the holding time of thermal pretreatment and the copper concentration in the residue and slag highlights the critical role of this parameter in the recycling process.

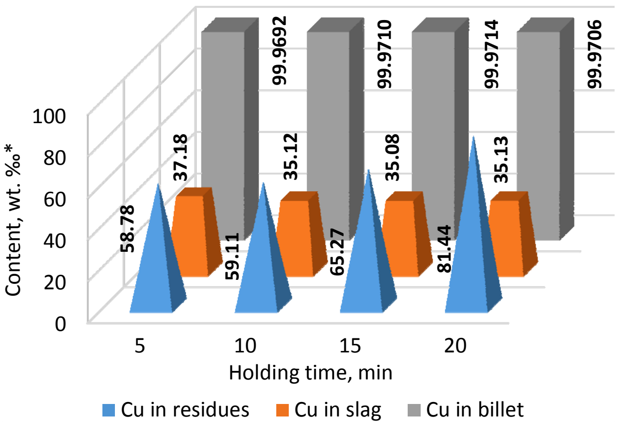

Figure 8. Copper content in residues, slag and billets as a function of holding time under equal-duration thermal stages; *copper content in billet is in wt. %

It should be noted that recycled copper scrap often contains various winding wires of different dimensions. In some cases, these wires can constitute all of the raw material (Fig. 1). Smaller diameter wires feature increased flexibility, making them particularly suitable for complex winding configurations. These enamelled wires are rated by their ability to withstand specific temperatures without degradation, with common classes including 130, 155, 180 and 220 °C. This classification allows them to be used in different environments with varying temperatures [21].

Table 3. XRF analysis for samples subjected to thermal pretreatment with equal holding times

Holding time, min	Compound, wt. ‰												
	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	P_2O_5	S	SiO_2	TiO_2	Cu	Pb	Zn
Residues													
5	1.31	1.59	0.75	0.88	1.05	0.01	1.23	0.07	1.33	0.09	58.78	0.04	0.07
10	1.38	1.65	1.30	0.88	0.83	0.07	1.88	0.07	1.33	0.09	59.11	0.05	0.13
15	1.38	1.73	1.81	1.21	0.16	0.10	3.16	0.15	1.52	0.08	65.27	0.06	0.19
20	1.39	1.94	1.85	1.21	0.16	0.10	3.21	0.34	1.51	0.07	81.44	0.05	0.25
Slag													
5	3.17	1.81	1.81	1.27	1.05	1.05	0.10	0.14	10.19	0.81	37.18	1.26	1.09
10	1.97	1.80	1.73	1.21	0.71	0.71	0.02	0.15	8.87	0.28	35.12	1.31	1.13
15	1.38	1.59	0.95	0.98	0.44	0.44	0.01	0.07	6.08	0.25	35.08	1.23	1.18
20	1.23	1.59	0.95	0.98	0.43	0.43	0.01	0.03	6.05	0.12	35.13	1.23	1.10

Therefore, the increased presence of copper in the residues is mainly attributed to the thermal degradation of small-sized winding wires. This degradation is visually confirmed by the clear presence of winding wire fragments in the residues corresponding to holding times of 15 and 20 minutes (Fig. 9). This observation highlights the importance of strategically managing holding time to improve the efficiency of the process. Moreover, these analyses clearly confirm the volatile and oxidising nature of the aforementioned impurities: phosphorus (P), zinc (Zn) and antimony (Sb). More specifically, a reduction in zinc content ranging from 7.1 to 9.6 wt. % was noticed in the values presented in Table 2 compared to those in Table 1.

Figure 9. Residual coil wires noticed in the slag after 15-minute test thermal pretreatment

In the thermal pretreatment process with equal holding times, the 15-minute hold produces the highest copper content of 99.9714 wt. % (Fig. 8). This represents an increase of 0.0004 wt. % compared to the content obtained with the 10-minute hold, and 0.0008 wt. % compared to the content obtained with the 20-minute hold. For copper concentration of 99.9714 wt. %, obtained with a 15-minute holding time, the total duration of the thermal pretreatment sequence is estimated at 140 min. Compared to the durations of 10-minute (102 min) and 20-minute (163 min) holds, there is a 37.25 % increase and a 14.12 % decrease, respectively.

As mentioned previously, thermal pretreatment with 15-minute hold intervals caused significant copper loss due to wire degradation. To solve this problem, four different thermal pretreatments with varying hold times (Fig. 4) are tested. Compared to the process with 10-minute hold intervals, three of these thermal pretreatments with sequences of 5−5−10−10−15−15, 5−10−10−15−15−5, 5−10−15−15−10−5 minutes gave similar results. These results were marked by an increase of 2 to 3 minutes in duration and a decrease in copper concentration of 0.0007 wt. %. This value represents the difference between the copper content obtained with a 10-minute hold intervals (99.9710 wt. %) and the average copper content from these three sequences, which was 99.9703 wt. %. However, the last sequence (5−5−10−10−15−5 minutes) proved to be particularly interesting. It delivered equivalent performance in terms of residue and slag mass loss compared to the 10-minute sequence. Additionally, it achieved a significant reduction in refining time of 8 minutes and an increase in copper concentration reaching 99.9716 wt. %, representing a gain of 0.0006 wt. % compared to the 10-minute sequence.

Table 4. XRF analysis for samples subjected to thermal pretreatment with varying holding times

Sequence, min	Compound, wt. ‰												
	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	P_2O_5	S	SiO_2	TiO_2	Cu	Pb	Zn
Residues													
5−5−10−10−15−5	1.38	2.04	1.30	1.01	1.05	0.07	1.74	0.23	1.47	0.09	58.97	0.05	0.16
5−5−10−10−15−15	1.38	1.77	1.32	1.21	1.01	0.01	2.03	0.11	1.33	0.09	59.34	0.07	0.16
5−10−10−15−15−5	1.41	1.65	1.29	1.21	1.02	0.03	1.98	0.10	1.17	0.09	59.18	0.06	0.14
5−10−15−15−10−5	1.37	1.76	1.32	1.16	1.01	0.07	1.96	0.09	1.38	0.08	59.41	0.06	0.16
Slag													
5−5−10−10−15−5	2.44	1.87	1.82	1.33	1.01	0.09	1.82	–	8.51	0.49	35.03	1.27	1.19
5−5−10−10−15−15	1.91	1.73	1.62	1.12	0.66	0.02	1.34	–	7.17	0.42	36.02	1.27	1.12
5−10−10−15−15−5	2.18	1.77	1.73	1.03	0.73	0.01	1.62	0.09	8.48	0.38	36.01	1.27	1.13
5−10−15−15−10−5	1.91	1.62	1.62	1.13	0.64	0.02	1.67	–	8.48	0.40	35.14	1.27	1.13

The results of XRF analysis of residues and slag from thermal pretreatment with varying holding times clearly demonstrate their effectiveness in minimising the presence of copper in the treated sample residue (Table 4). This reduction in copper content has significantly contributed to the results obtained by these refining processes in terms of purification, as shown in Figure 10.

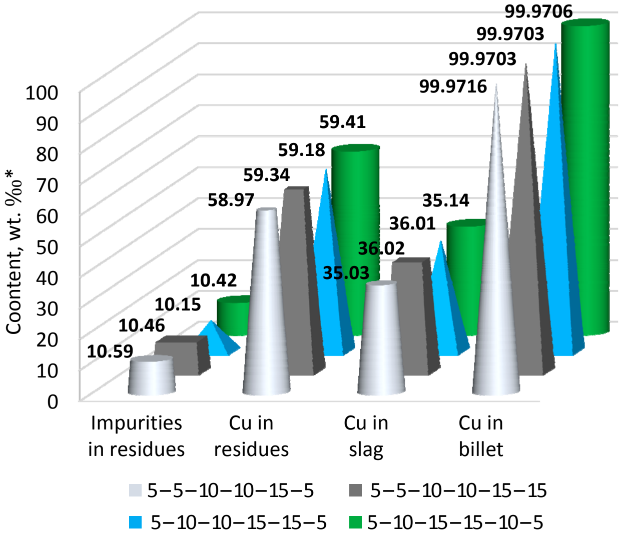

Figure 10. Quantitative data on thermal pretreatment with varying holding times; *copper content in billet is in wt. %

3.3 Thermal and electrical conductivity

The temperatures required to determine the thermal conductivity of the billet, cast from the sample that underwent thermal pretreatment in the sequence 5–5–10–10–15–5, were measured experimentally under varying voltages (Table 5). These temperatures correspond to the hot and cold surfaces of the copper sample, as measured by thermocouples in direct contact with the disc during the conductivity test.

Using Equation (1), the average thermal conductivity of this billet can be estimated at 362 W/mK (Table 6). The disc samples had the same cross-sectional area of 4.906×10^{-4} m^2, but their thicknesses varied slightly due to manual cutting.

Table 5. Experimental values used to calculate the thermal conductivity of the billet cast from a sample with pretreatment sequence 5–5–10–10–15–5

U, V	42	55	68	70	91
I, A	0.042	0.055	0.068	0.070	0.092
T_1, °C	25.6	28.2	31.4	32.5	39.9
T_2, °C	25.2	27.5	30.3	31.3	38.0
T_3, °C	24.7	26.8	29.3	30.1	36.1
T_6, °C	22.4	23.0	23.7	24.1	26.0
T_7, °C	22.0	22.3	22.8	23.1	24.4
T_8, °C	21.7	21.7	21.9	22.1	22.9

By applying the Wiedemann-Franz law and Equation (2) at a temperature of 20 °C, the electrical conductivity of copper was estimated to be approximately 55.1×10^6 S/m, which is an improvement over previous values reported in the study [20]. To substantiate this theoretical estimation with experimental evidence, electrical conductivity measurements were conducted on three samples using the Ecopia Hall effect measurement system HMS-5300 (Table 7). Measurements 1 to 4 correspond to four repeated electrical conductivity measurements taken under the same conditions on three different copper sample billets.

Out of the twelve measurements conducted, only three produced values aligning with the theoretical conductivity expected for copper of 99.974 wt. % purity. These three measurements (54.17×10^6, 54.50×10^6 and 55.41×10^6 S/m) were averaged to yield a mean conductivity of 54.7×10^6 S/m. The measurements with lower values were attributed to variability in contact resistance and were consequently excluded from the calculated mean. The resulting average electrical conductivity closely aligns with the theoretical prediction, confirming the validity of the theoretical estimation and remaining consistent with recent literature data [21,22,25].

Table 6. Thermal conductivity of a billet cast from a sample with pretreatment sequence 5–5–10–10–15–5

ΔX, m	UI, W	T_{hot}, K	T_{cold}, K	ΔT, K	$\Delta T/\Delta X$, K/m	K, W/mK
1.80×10^{-2}	17.64	24.45	22.60	1.85	102.54989	350.60145
1.02×10^{-2}	30.25	26.45	23.35	3.10	171.84035	358.79844
2.02×10^{-2}	46.24	28.80	24.15	4.65	257.76053	365.63834
3.02×10^{-2}	49.00	29.50	24.60	4.90	271.61863	367.69427
4.02×10^{-2}	83.72	35.15	26.80	8.35	462.86031	368.66304

Table 7. Electrical conductivity of a billet cast from a sample with pretreatment sequence 5−5−10−10−15−5

	Measurement × 10^6, S/m			
	1	2	3	4
Sample 1	28.82	28.47	54.17	38.79
Sample 2	20.90	26.87	40.66	54.50
Sample 3	28.02	55.41	23.03	22.81

These results, which are consistent with those mentioned in our previous study [20], highlight the quality of the purification process tested. Pretreatment with the 5−5−10−10−15−5 sequence considerably improved thermal and electrical conductivities. This improvement, reflected by a thermal conductivity of approximately 362 W/mK and an electrical conductivity of 54.7 × 10^6 S/m, extends the possibilities for industrial use of the copper produced, particularly in the manufacture of certain types of electrical wire.

4. Conclusion

This work demonstrates that applying a controlled thermal pretreatment to copper scrap significantly improves refining performance. Starting from an initial purity of 99.9230 wt. % (untreated billet), the optimised sequence 5−5−10−10−15−5 increased the copper content to 99.9716 wt. %. This confirms the potential of thermal pretreatment to enhance the quality of molten copper, highlighting its importance in the purification process through the exploitation of the volatility of certain impurities and the oxidation of others to form slag under ambient conditions.

Additionally, the thermal conductivity reached approximately 362 W/mK and electrical conductivity was measured at 54.7 × 10^6 S/m, both aligning with industrial-grade copper standards. The refining time was also reduced by over 30 %, from 140 minutes using an equal 15-minute hold intervals to 94 minutes, while maintaining low mass losses similar to shorter sequences. These improvements suggest that this pretreatment process offers an effective balance between purity, energy/time efficiency and material recovery. This approach optimises both the quality of the copper and the operational efficiency of the recycling process while producing a product with a wide range of industrial applications.

References

[1] L. Ciacci, T. Fishman, A. Elshkaki, T.E. Graedel, I. Vassura, F. Passarini, Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28, Global Environmental Change, Vol. 63, 2020, Paper 102093, DOI: 10.1016/j.gloenvcha.2020.102093

[2] V. Stratiotou Efstratiadis, N. Michailidis, Sustainable recovery, recycle of critical metals and rare earth elements from waste electric and electronic equipment (circuits, solar, wind) and their reusability in additive manufacturing applications: A review, Metals, Vol. 12, No. 5, 2022, Paper 794, DOI: 10.3390/met12050794

[3] K. Born, M.M. Ciftci, The limitations of end-of-life copper recycling and its implications for the circular economy of metals, Resources, Conservation and Recycling, Vol. 200, 2024, Paper 107318, DOI: 10.1016/j.resconrec.2023.107318

[4] J. Wang, Y. Ju, M. Wang, X. Li, Scenario analysis of the recycled copper supply in China considering the recycling efficiency rate and waste import regulations, Resources, Conservation and Recycling, Vol. 146, 2019, pp. 580-589, DOI: 10.1016/j.resconrec.2019.02.008

[5] M. Wędrychowicz, J. Kurowiak, T. Skrzekut, P. Noga, Recycling of electrical cables – Current challenges and future prospects, Materials, Vol. 16, No. 20, 2023, Paper 6632, DOI: 10.3390/ma16206632

[6] L. Brooks, G. Gaustad, Positive material identification (PMI) capabilities in the metals secondary industry: An analysis of XRF and LIBS handheld analyzers, in C. Chesonis (Ed.), Light Metals 2019, Springer, Cham, 2019, pp. 1375-1380, DOI: 10.1007/978-3-030-05864-7_170

[7] A. Loibl, L.A. Tercero Espinoza, Current challenges in copper recycling: Aligning insights from material flow analysis with technological research developments and industry issues in Europe and North America, Resources, Conservation and Recycling, Vol. 169, 2021, Paper 105462, DOI: 10.1016/j.resconrec.2021.105462

[8] W. Liu, B. Ma, Z. Zhou, Y. Zuo, L. Wang, Y. Chen, C. Wang, Efficient separation of impurities in scrap copper by sulfurization-vacuum distillation, Vacuum, Vol. 202, 2022, Paper 111145, DOI: 10.1016/j.vacuum.2022.111145

[9] M. Mominul Haque, H. Kim, M.-S. Kong, H.-S. Hong, K.-S. Kim, C.S. Lee, Recycling copper from waste copper wire using an applied voltage, International Journal of Precision Engineering and Manufacturing, Vol. 13, No. 7, 2012, pp. 1251-1254, DOI: 10.1007/s12541-012-0167-3

[10] Y. Fu, J. Chen, N. Liu, Y. Lu, T. Li, G. Yin, Study of ultrahigh-purity copper billets refined by vacuum melting and directional solidification, Rare Metals, Vol. 30, No. 3, 2011, pp. 304-309, DOI: 10.1007/s12598-011-0388-0

[11] A. Smalcerz, L. Blacha, Removal of lead from blister copper by melting in the induction vacuum furnace, Archives of Foundry Engineering, Vol. 20, No. 2, 2020, pp. 84-88, DOI: 10.24425/afe.2020.131307

[12] N.K. Dosmukhamedov, E.E. Zholdasbay, G.B. Nurlan, Ultra-pure Cu obtaining using zone melting: influence of liquid zone width on impurities' behavior, Non-ferrous Metals, Vol. 43, No. 2, 2017, pp. 15-20, DOI: 10.17580/nfm.2017.02.03

[13] J. Liu, Y. Yang, B. Li, Y. Wei, Phase transformation of impurity elements and high-efficiency impurity removal in complex copper concentrate smelting process, Mining, Metallurgy & Exploration, Vol. 40, No. 5, 2023, pp. 1639-1653, DOI: 10.1007/s42461-023-00827-w

[14] W. Blanco-Vino, J.I. Ordóñez, P. Hernández, Alternatives for copper anode slime processing: A review, Minerals Engineering, Vol. 215, 2024, Paper 108789, DOI: 10.1016/j.mineng.2024.108789

[15] Z.H.I. Sun, Y. Xiao, J. Sietsma, H. Agterhuis, Y. Yang, Complex electronic waste treatment – An effective process to selectively recover copper with solutions containing different ammonium salts, Waste Management, Vol. 57, 2016, pp. 140-148, DOI: 10.1016/j.wasman.2016.03.015

[16] D. Wang, L. Wang, H. Yu, Y. Tian, B. Yang, B. Xu, D. Liang, T. Ma, Preparation of high-purity copper through vacuum distillation, Vacuum, Vol. 218, 2023, Paper 112566, DOI: 10.1016/j.vacuum.2023.112566

[17] J. Ryter, X. Fu, K. Bhuwalka, R. Roth, E.A. Olivetti, Emission impacts of China's solid waste import ban and COVID-19 in the copper supply chain, Nature Communications, Vol. 12, 2021, Paper 3753, DOI: 10.1038/s41467-021-23874-7

[18] Morocco waste and scrap, copper or copper alloy exports by country in 2022, available at: https://wits.worldbank.org/trade/comtrade/en/country/MAR/year/2022/tradeflow/Exports/partner/ALL/product/740400, accessed: 20.07.2025.

[19] J.Y. Choi, D.S. Kim, Production of ultrahigh purity copper using waste copper nitrate solution, Journal of Hazardous Materials, Vol. 99, No. 2, 2003, pp. 147-158, DOI: 10.1016/S0304-3894(02)00312-6

[20] O. Choukri, M. Ez-zine, S. Taibi, Achieving industrial-grade purity in recycled copper scrap: Pretreatment and fire refining approach, Tribology and Materials, Vol. 4, No. 2, 2025, pp. 78-89, DOI: 10.46793/tribomat.2025.008

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

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

[23] D.W. Green, M.Z. Southard (Ed.), Perry's Chemical Engineers' Handbook, McGraw-Hill Education, New York, 2019.

[24] Copper production, in S. Seetharaman (Ed.), Treatise on Process Metallurgy, Volume 3: Industrial Processes, 2014, pp. 534-624, DOI: 10.1016/B978-0-08-096988-6.00027-4

[25] N.N. Greenwood, A. Earnshaw (Eds.), Chemistry of the Elements, Butterworth-Heinemann, Oxford, 1997, DOI: 10.1016/C2009-0-30414-6