Numerical and Experimental Study of a Thermal Separation Process, for Electrical Cable Waste Components

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Abstract: The continuous update of electrical products and the rapid development in the power industry are leading to an increase in cable waste. Due to the high purity of copper in cables and the low energy consumption when they are recycled, waste cables are a valuable source of raw materials for the reclaimed metal industry. However, achieving complete separation between the metal and the insulator, in recycling electrical cable waste, has always been a challenge. This paper presents an original approach to liberating the metal conductor from the insulator, without shredding the cables into small pieces and using subsequent multistep separation processes. A cable is passed between two rollers that rotate at the same speed. The outer surface of one roller is heated below the melting point of the thermoplastic insulator; the other roller remains at room temperature. The stripping process was studied through both numerical simulations and experiments. A methodology for numerical simulation of the cable stripping process is proposed, using SolidWorks Simulation software. In addition, a prototype of the cable stripping machine was designed and built. Numerical simulations revealed that the insulator, with lower thermal conductivity than the conductor, heats unevenly, resulting in a bending of the insulator and the subsequent exposure of the metal conductor. Experimental findings show that the optimal peripheral speed of the rollers for achieving complete separation, depends on the thickness of the insulator and decreases by 4.5 times, as the thickness increases 1.8 times.

Keywords: conductor; copper; PVC insulator; temperature; thermal deformations; waste cable

1 Introduction

Electrical cables represent a significant part of electronic and electrical waste; in Sweden alone, approximately 40000 tons of cables and wires are discarded each year [1]. Therefore, it is essential to find reliable and efficient recycling solutions [2-4]. Cable waste can be produced during the cable manufacturing process (for instance, cables rejected due to wire or insulation material defects) or as end-of-life products (for instance, cables remaining after building repairing work). The most valuable components of cable waste that can be reused are expensive non-ferrous metals like aluminum and copper. Copper is considered one of the most important industrial metals, with approximately 70% of global copper being used for various electrical applications [5] [6]. Furthermore, polymeric insulators such as polyethylene, polyvinyl chloride (PVC), etc. can be granulated and recycled. Studies have shown that polymeric insulated cable waste typically contains 40 to 90 weight percent metals [7]. However, physical separation of the insulator and conductor is required to recover these two components [3]. This has always caused some problems.

In the past, polymeric insulators were often removed from the metal conductor by burning [8] [9]. The conductor remained after burning and then could be collected. Although cable burning is efficient and straightforward, it cannot be used in most countries due to environmental concerns such as the release of harmful gases (for example, hydrogen chloride), dust, and heavy metals into the environment [8-10]. Furthermore, recycling only metals without considering insulator recovery is economically impractical.

Pyrolysis is considered a promising method for recycling cable hoses [11]; however, it relies on external fuel and its energy efficiency is suboptimal [12]. Corrosion problems in pyrolysis reactors are also reported due to the generation of hydrochloric acid during the pyrolysis of PVC [13].

Most of the current cable waste recovery processes involve room-temperature multistep shredding of cables into smaller pieces to improve the liberation of the metal conductor from the insulation material. As a result of the shredding process, some impregnation of the insulation material with metal particles occurs. Then it is difficult to separate impregnated metals from the insulation material. Various technologies, including vibrating or air tables, electrostatic separators, etc., are used to separate metals from plastic [9, 14, 15], but metal recovery could be improved as it is less than 100% in most cases [16]. Other physical separation methods, such as sieving, are less efficient in separating fine materials [5].

In the cryogenic shredding process, the cable waste is treated with liquid nitrogen to make the insulation material brittle. After liberation, the metal is separated from the insulation material utilizing differences in magnetic and conductive properties or differences in density. This shredding process did not find wider application due to the high cost of cryogenic equipment [9].

Chemical methods, such as copper cementation on less noble metals (iron, aluminum) and electrowinning, can be used to extract the metal from the solution [17] [18], but they generate hazardous waste.

Thermal cable waste component separation methods, which do not require shredding the cable into small pieces, rely on thermal impact and difference in thermal conductivity between the conductor and insulation material [3] [8]. By one of these methods, the cables are cut into suitable length pieces and placed in a bath with hot water [8]. By controlling the cutting length, mixing speed, and water temperature, complete liberation was achieved.

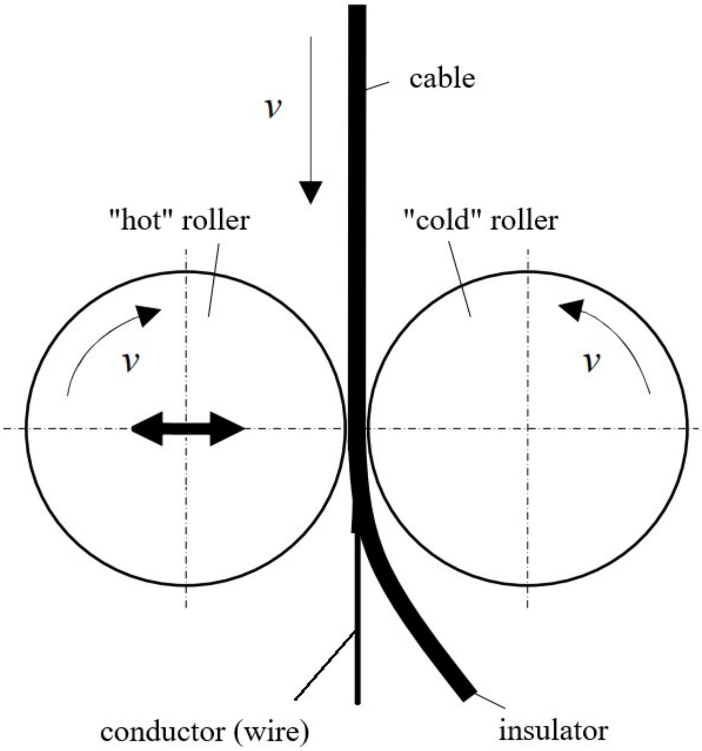

Figure 1

Schematic diagram representing the thermal cable stripping method: *v* – cable linear speed (roller peripheral speed)

In this work, an original thermal method is proposed to remove the insulation material from the metal conductor. The cable passes between two rollers rotating at the same speed *v*, as shown in Figure 1. The outer surface of one roller is heated below the melting point of the thermoplastic insulator, while the other roller remains at room temperature. The cable conductor breaks through the insulator due to the total impact of thermal deformation of the insulation material and softening of the insulation material caused by the heat. This method allows for the recovery of single-core cables of various diameters, lengths, and materials. In waste preparation, simply straightening the cable by hand is often sufficient. The method can be automated using guiding and feeding equipment to avoid cutting the cable into pieces. The metal conductor separates completely from the insulation material without damage. The removed insulation material is absolutely metal-free; thus, the problem of contamination of the insulation material with metal particles, which occurs when the cables are shredded [3] [8], is solved.

2 Experimental

The top view of the experimental cable stripping machine is shown in Figure 2. AC Electric motor 1 rotates rollers 4 and 5 through belt drive 2 and gearbox 3. Rollers 4 and 5 rotate in the same direction and at the same rotational speed. With identical diameters (89 mm), their peripheral speeds are also equal. The rotational speed of the rollers (or cable speed *v*) is controlled by a variable frequency drive connected to the electric motor 1. The frequency drive is not shown in Figure 2.

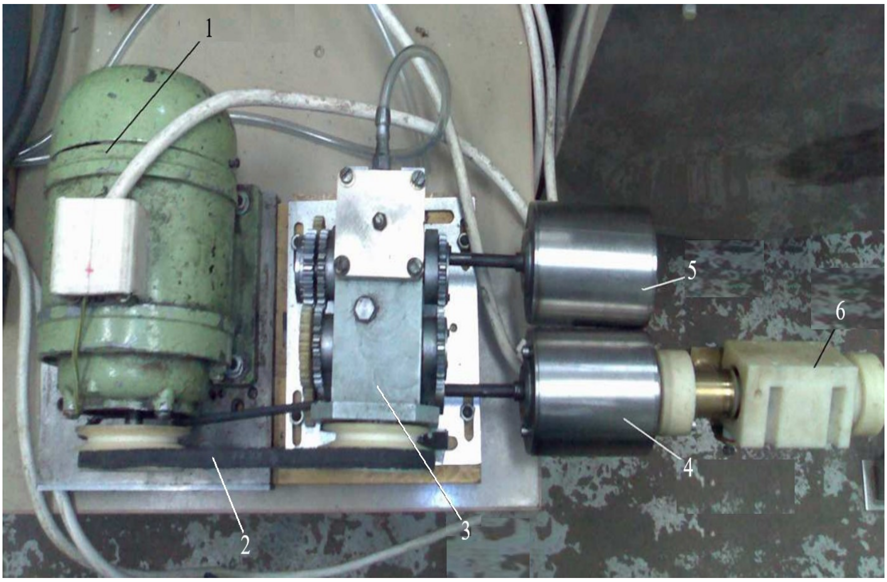

Figure 2
Experimental cable stripping machine: 1 – electric motor; 2 – belt; 3 – gear box; 4 – “hot” roller; 5 – “cold” roller; 6 – current collector

The surface of “hot” roller 4 is electrically heated through current collector 6 (Figure 2). The outer surface temperature of roller 4 can be varied to 250 °C; it is controlled by a contact thermometer. A pneumatic cylinder inside gearbox 3 lightly presses the rollers against each other. Rollers 4 and 5 have work surfaces made of high manganese stainless steel to minimize insulation material adhesion.

Table 1

Properties and composition of tested cables

Outer diameter, mm	Copper wire diameter, mm	Thickness of the PVC insulation material, mm	Copper, by weight%	PVC, by weight%
3	1.8	0.6	82	18
4.4	2.8	0.8	83.5	16.5
6.8	4.6	1.1	86.2	13.8

Copper single-core polyvinyl chloride insulated cables with various conductor diameters and insulator thicknesses were tested to determine the optimal speed *v* (Figure 1) for complete insulation removal. The properties of the cables tested are provided in Table 1. The cables, cut into approximately 1.5 m long pieces, were passed between rotating rollers. One roller was heated to 160 °C, while the other remained at room temperature.

The quality of insulator removal was visually controlled. If incomplete removal of the insulator occurred, the roller speed was reduced and the test was repeated until complete removal was achieved. The speed at which complete removal was observed was considered optimal for this cable. Each test was repeated five times at optimal speed to minimize the impact of random errors on the results.

3 Numerical Simulation

The removal process of the insulator was simulated using SolidWorks Simulation software. The 3D model created using the SolidWorks CAD software is presented in Figure 3. The properties of the materials of the model components selected from the SolidWorks materials library [19] are presented in Table 2.

First, a thermal study was performed and the distribution of temperature in various components of the model was obtained. The thermal exposure time was taken according to the cable speed. Second, the thermal loads were transferred to static structural analysis and the deformations of the conductor and the insulator were calculated. Both thermal and static analysis were performed using SolidWorks Simulation software. The model was meshed with three-dimensional tetrahedral finite elements. The total number of finite elements is 46838, and the number of nodes is 73547. The model is characterized by 38062 degrees of freedom. Numerical analysis was performed using the FFEPlus solver.

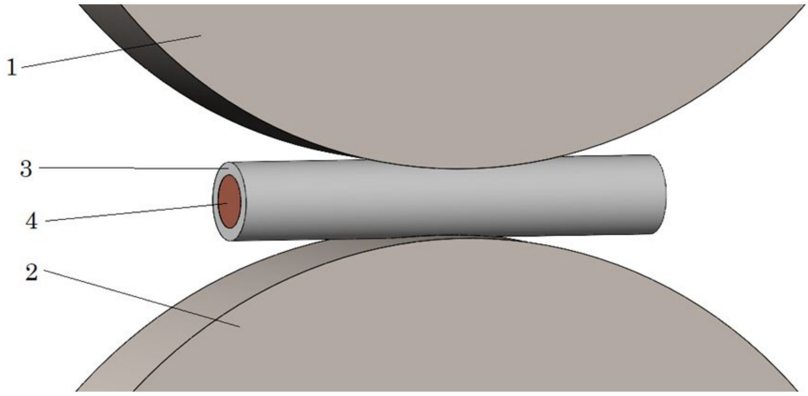

Figure 3
3D model of the insulator removal process: 1 – “hot” roller; 2 – “cold” roller; 3 – PVC insulator; 4 – copper conductor

Table 2
Material properties selected from SolidWorks materials library

Component (Figure 3)	Elasticity modulus, MPa	Poisson’s coefficient	Thermal expansion coefficient, K^{-1}	Thermal conductivity, W/(mK)	Specific heat, J/(kgK)
Insulator (PVC)	6	0.47	$5.2 \cdot 10^{-5}$	0.25	1600
Conductor (copper)	110000	0.37	$1.7 \cdot 10^{-5}$	400	380
Roller (steel)	200000	0.28	$1.3 \cdot 10^{-5}$	50	460

4 Results and Discussion

The distribution of temperature within the components of the model is presented in Figure 4.

As shown in Figure 4, the temperatures within the conductor and insulator differ significantly due to their different thermal conductivities. The temperature of the upper side of the PVC insulator reaches the maximum temperature of the “hot” roller (160 °C), while the bottom side remains cold (~30 °C). Moreover, the insulator's temperature rapidly decreases upon leaving the contact zone with the “hot” roller. On the contrary, the temperature inside the conductor is evenly distributed, reaching 51 °C except on the bottom side, where it varies from 47 to 49 °C. This effect is attributed to the higher thermal conductivity of copper compared to the PVC insulator (Table 2).

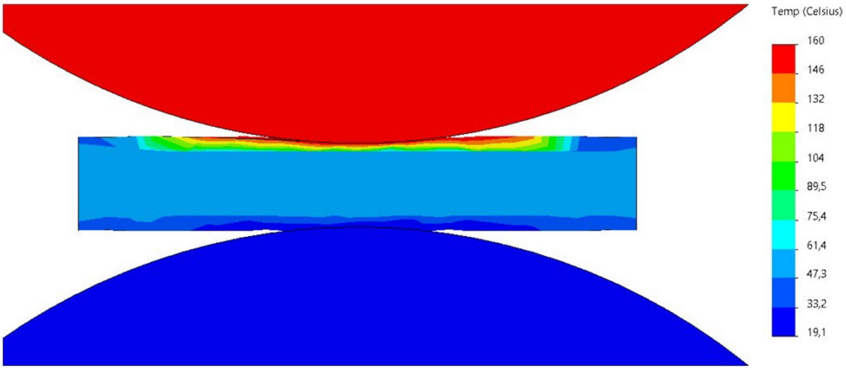

Figure 4
Distribution of the temperature inside the rollers and the copper core cable
(outer diameter of the cable – 6.8 mm)

To determine the deformations of the model components, a static structural analysis was performed. The deformed shape of the insulator and conductor is presented in Figure 5. One end of the cable was constrained from any motion; also, the contacts between the rollers and the cable were verified.

Figure 5 shows that the equivalent strains (ESTRN) of the insulator are significantly higher than those of the conductor. Due to the uneven heating of the PVC insulator, it bends, while the conductor maintains its shape with slight lengthening attributed to an even temperature distribution inside. The bending and softening of the insulation material cause the conductor to break through.

Table 3 presents the average temperature of the conductor, the maximum equivalent strain of the insulator, and the longitudinal strain of the conductor values for various cables.

For comparison, Table 4 presents the temperature and deformation values obtained for the same cables with an aluminum conductor instead of copper. It can be seen that the components of the cables are deformed in a similar way to the copper ones.

Table 3
Obtained temperatures and deformation (copper wire)

Outer diameter of the cable, mm	**Average conductor temperature, °C**	**Maximum longitudinal strain of the conductor**	**Maximum equivalent strain of the insulator**
3	61.4	0.0028	0.111
4.4	52.1	0.0024	0.027
6.8	51.1	0.0015	0.0129

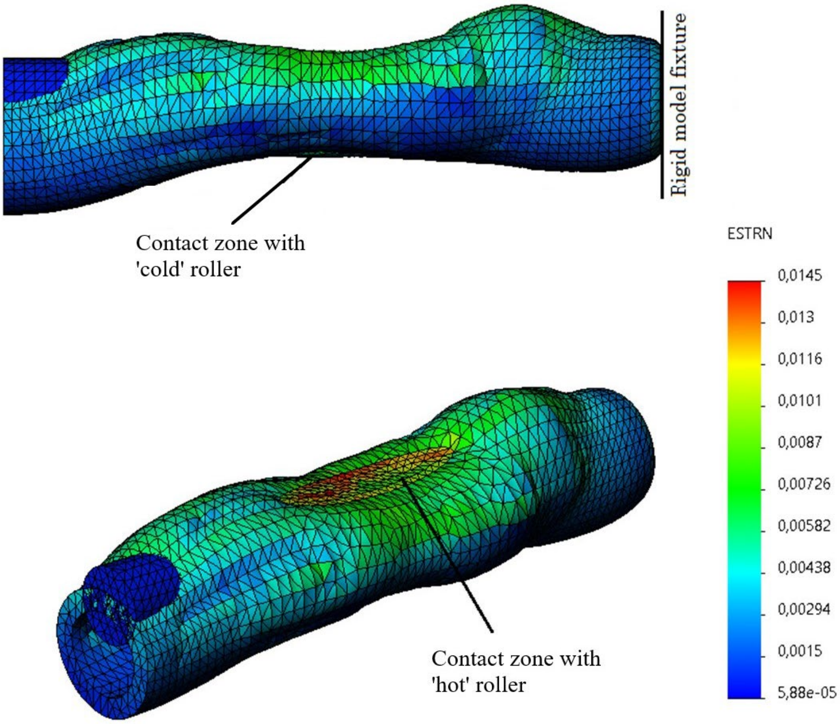

Figure 5
Deformed shape of the copper core cable (outer diameter of the cable – 6.8 mm)

Table 4
Obtained temperatures and deformation (aluminum wire)

Outer diameter of the cable, mm	**Average conductor temperature, C°**	**Maximum longitudinal strain of the conductor**	**Maximum equivalent strain of the insulator**
3	63.3	0.0034	0.119
4.4	60.5	0.0031	0.031
6.8	59.3	0.0016	0.0127

The results of the experimental studies are presented in Figure 6 as the optimal average cable speed versus the thickness of the PVC insulation layer of the copper single-core cable. Figure 6 indicates that as the thickness of the insulator increases from 0.6 to 1.1 mm, the optimal cable speed required for complete insulation material removal decreases from 1.8 to 0.40 m/min (the rotational speed of the rollers decreases from 6.45 to 1.43 rpm).

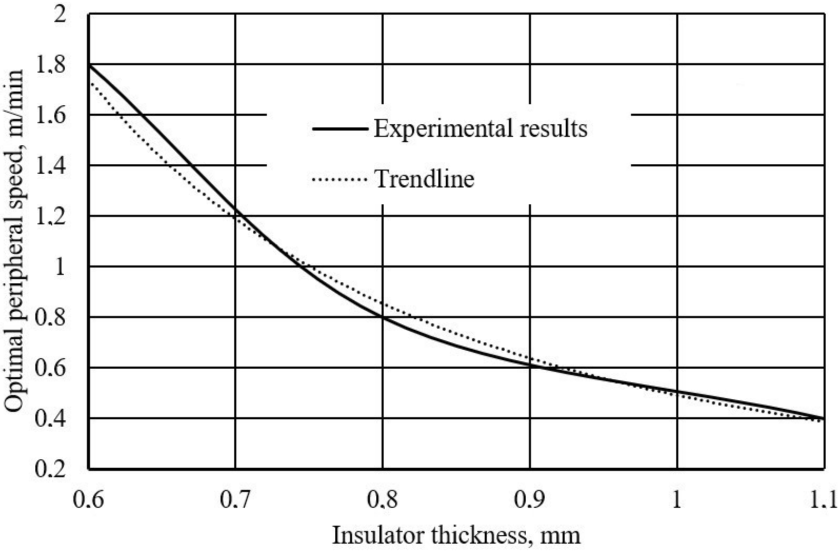

Figure 6
Optimal peripheral speed of the rollers (linear cable speed) as a function of the thickness of the insulator of the single copper core cable

The recovered copper and insulating material are completely separated and pure, both of which can be reused.

Complete liberation of the conductor from isolating material was also reported by the authors, who proposed another thermal method, where the waste cables were placed in a container with hot water [8]. However, the method is sensitive to the cable length/cross-section area ratio and requires its control to achieve complete separation [8]. With the two-roller method, it is enough to roughly straighten a cable of any length by hand.

It was found that the experimental results presented in Figure 6 can be approximated by the following equation:

$$v = 0.4912t^{-2.476} \tag{1}$$

where v is the optimal cable speed, m/min, t is the thickness of the PVC insulator, mm.

The power function (1) produced the best fit with a determination coefficient (R^2) value of 0.9958.

The obtained experimental results are in good agreement with the numerical simulation results presented in Figure 5, which shows that the conductor pierces the insulator.

Based on the data in Table 1 and the optimal speed values obtained experimentally, the cable stripping machine can theoretically strip 108 meters of 3 mm diameter (outer diameter, Table 1) cable per hour, 48 meters of 4.4 mm diameter cable per hour, and 24 meters of 6.8 mm diameter cable per hour. Considering the density of the copper conductor, the productivity values in units of mass are 2.46 kg/h, 2.64 kg/h and 3.57 kg/h, respectively.

Conclusions

The proposed "hot and cold" roller cable stripping machine is suitable for small waste recycling plants. One of the main advantages of the proposed machine, is the possibility of keeping the metal conductor of the cable undamaged and avoiding multistep shredding or other preparatory operations on waste cables.

The results of the numerical simulation indicate that the metal conductor is only slightly elongated, rather than bent, during the insulation removal process. This elongation does not significantly impact the thermal cable stripping process. The primary factor that influences the process is the deformation of the insulator, which heats unevenly due to its low thermal conductivity. This uneven heating causes the insulator to deviate in one direction, causing the conductor to break through it.

Experimental results demonstrate that the optimal peripheral speed of the rollers, or the linear cable speed needed to completely remove the PVC insulator from the copper conductor of the single-core cable, depends on the thickness of the insulator. When the thickness of the insulation material increases from 0.6 to 1.1 mm, the optimal peripheral speed of the rollers must be reduced from 1.8 to 0.4 m/min.

The recovered insulation material, after the separation process, is absolutely metal-free and can be recycled without any additional complex processing.

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