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A novel method based on thermal conductivity for material identification in scrap industry: An experimental validation

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ABSTRACT

Fast, accurate and reliable identification and sorting of materials is still a challenge in recycling sector. Scrap metals are often classified through density and colour, which cause notable financial burdens to the companies in most cases. Within the scope of this research, a novel method based on thermal conductivity is presented for material identification in scrap industry. The unit consists of a constant heat flux source and a cooling system, in which axial heat conduction is enabled and radial heat transfer is eliminated. For the steady-state conditions, temperature gradient across the sample metals is measured along with the constant heat flux value, and the thermal conductivity of the samples is determined via the Fourier's heat conduction law. Copper, brass and stainless steel samples are considered in this research to verify the accuracy of the results. For a reliable and scientific approach, three independent sets of experiments are conducted, and the results are evaluated in terms of accuracy and consistency. Experimental thermal conductivity values of the said samples are compared with the reported data in literature and a good accordance is achieved. Error in measurements is calculated to be 1.37, 3.31 and 4.46% for copper, brass and stainless steel sample, respectively which is acceptable. The tests are repeated with highly sensitive probes for aluminium sample, and the measurement error is calculated to be 0.56%.

1. Introduction

1.1. Scrap industry in terms of economic and environmental aspects

The depletion of natural resources is unequivocal as a consequence of developing economy, industry and growing population at global scale. The process of extracting virgin ores to manufacture ferrous and non-ferrous metals and the energy consumed for this purpose can be considered as primary reasons of resource depletion [1]. Scrap industry is in the centre of interest in recent years owing to the remarkable economic aspects of recycling sector. In this respect, three Rs (reduce, reuse, and recycle) are adopted to protect the natural resources consumed wastefully by governments and non-government organizations [2]. Especially recycling is of vital importance in terms of economic and environmental issues since it is capable of mitigating energy consumption and the amount of scrap metals [3,4].

The shift to recycling process, called as secondary production, noticeably grows year after year through the increasing quantities of scrap metals reused in manufacturing industries [5]. In addition, material supply chains through "close the loop" encourage firms, researchers, and policymakers to collect and reuse scrap metals effectively in some countries facing lack of natural resources such as EU and Japan [6]. Novel recycling technologies draw the attention of metal manufacturers to consume less energy and raw materials throughout the production. It is a common view that the cost of metals in market can be notably reduced by means of scrap metals recycled [7].

The metal-recycling process consists of six main stages as collection, sorting, shredding, physical separation, hydrometallurgical treatment, and smelting. Several techniques are used to carry out the scrap sorting processes such as X-ray transmissions, apparent density and 3D sensing [8,9]. Current available techniques have some challenges regarding cost, accuracy, reliability and process time. Therefore, additional techniques are highly required for fast, accurate and reliable identification and sorting of materials. From this point of view, a novel method based on thermal conductivity is presented in this research for material identification in scrap industry.

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1.2. Sorting of materials in scrap industry through thermal conductivity

Reliable and accurate identification and sorting of materials is of vital importance in scrap industry since incorrect material determination in buying and selling of scrap metals might cause notable financial losses and market insecurity. Thermal conductivity, which is a characteristic property of materials, is considered as a key solution in scrap industry for a fast, low-cost and eco-friendly material identification [10]. Thermal conductivity is not directly measurable and therefore, there are several experimental techniques in literature to determine the thermal conductivity of materials. The definition of thermal conductivity and the mathematical theory of heat conduction is first presented by French mathematician and physicist Jean Baptiste Fourier (1768–1830) who is able to achieve a general differential equation for heat conduction as follows:

$$Q_x = -kA\frac{dT}{dx}$$

where Q_x is the heat transfer rate [W], A is the cross-sectional area normal to direction of heat flow [m^2], dT/dx is the temperature gradient across the material [K/m] and k is the thermal conductivity of the material [W/mK]. Some experimental methods for sorting of scrap metals used from 1800 to 1900 are listed in Table 1 and the apparatuses are shown in Fig. 1 [11]. It is achieved from the literature data that there are no noticeable improvements in measurement techniques at the beginning of the 20th century [12]. After the second world war, notable advancements are observed in industry and more demands to metals like iron, copper, nickel, aluminum take place. For the more efficient use of the limited resources and for the efficient recycling processes of materials, numerous attempts are made for reliable material identification and sorting of scrap metals. As a consequence of this, new techniques are developed to determine the thermal conductivity of the scrap materials. One of these methods is the hot wire technique. This technique, which has an accuracy in the range of 5–10%, is mostly applied to molten metals, so it is not possible to use in most of the industrial sectors. Another measurement method is the laser-flash technique which has some challenges such as long time requirement for reliable measuring, large sample sizes and high temperature measurements. The accuracy of laser-flash technique is reported to be about 3% [13]. The Three-ω technique, which is initially used for measuring the thermal conductivity of bulk samples, is extended to different types of materials by time. But this method has 5% accuracy which is not suitable for sensitive analyses [14,15].

1.3. Goal of the research

Through the literature survey, it can be easily concluded that material identification and sorting of scrap metals is a vital process, and current available systems have some challenges regarding cost, reliability and process time. Therefore, within the scope of this research, a novel method based on thermal conductivity for material identification in scrap industry is presented, and the accuracy and the reliability of the new design is verified through several independent tests conducted on different scrap metal samples. The three most common materials (copper, brass, stainless steel) in the scrap industry are considered in the research, and the tests are conducted through conventional K-type thermocouples. Following the acceptable accuracy range from the measurements, the tests are repeated with highly sensitive temperature sensors (SK-S104K high sensitivity probes) for an additional aluminium sample, and a very good accuracy is achieved. Overall, the goal of the research can be expressed as devising, fabricating and testing a novel measurement system for identifying scrap metals in recycling industry through a low-cost, effective and eco-friendly approach based on thermal conductivity.

Table 1
Thermal conductivity measurement systems for sorting of scrap metals [11].

	Apparatuses	Absolute Errors
Relative conductivities	Wiedeman and Franz's apparatus	90–95%
Absolute conductivities	Gray's apparatus	3–6%
The guard-ring	Berget's apparatus	9–17%
Steady-state heat flow	Forbes's apparatus	80%

2. Experimental

2.1. Description of the measurement system

A novel experimental setup based on thermal conductivity for identifying scrap metals in a fast, reliable and low-cost manner is devised, constructed and tested within the scope of this research. The whole system basically consists of four main parts which are cylindrical propylene body, DC power source, constant temperature bath and data-logging system. 3D sketch and experimental setup with the measurement devices are illustrated in Fig. 2. The setup can be expressed as a successful application of Fourier's heat conduction law. The core of the system is the cylindrical propylene body in which the axial heat conduction takes place across the scrap metal samples. Through the fact that the heat transfer occurs when the temperature difference is available inside the material, a resistance wire unit which is in good contact with the scrap sample at the top is utilised for the hot side, and a direct contact heat exchanger driven by a constant temperature bath which is integrated with the sample at the bottom is considered for the cold side. For a constant value of DC voltage adjusted by a DC power unit, a certain value of DC current flows over the resistance wire which yields a constant electrical power. Since the whole system is well-insulated, radial heat transfer is prevented due to adiabatic boundary condition, and axial heat conduction takes place only across the scrap metal samples. In other words, a linear relationship between axial temperature and sample length occurs. This can be easily justified through the heat conduction equation. In Cartesian coordinates, the general form of the 3D heat conduction in a solid is given as follows:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

As the heat conduction takes place only in x direction and there is no heat generation inside the solid, the general form of heat equation is simplified into the following equation for steady-state conditions:

$$\frac{\partial^2 T}{\partial x^2} = 0$$

Since the temperature is only dependent on the axial distance, the differential equation can be expressed in ordinary differential equation form as follows:

$$\frac{d^2 T}{dx^2} = 0$$

The solution of this ordinary differential equation can be easily achieved as given below:

$$T(x) = C_1 x + C_2$$

The solution guarantees a linear relationship between axial temperature and axial distance as expected. Three samples are placed inside the propylene body from top to bottom, which are made of copper, stainless steel and brass. The samples are connected with highly conductive thermal paste, and the bolted joint is considered to minimise surface resistance effects. Axial temperatures are measured from five different points for copper and brass samples and from two different points for stainless steel sample. Copper and brass samples have the same length of 50 mm, whereas the stainless steel sample is 20 mm. The diameter of each sample is 20 mm as well. The reason of selecting such a small sample length for stainless steel is that the said dimension is