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Metal Separator for Copper and Stainless Steel

Final Thesis

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Abstract

The project's background is based on a task from the company Danfoss. Danfoss' objective was to find a solution for sorting scrap metal. The task was to find a solution or possibly invent a new solution for the separation of waste. However the project was carried out independently of Danfoss, as they have received a short report in which they have found all the information they need and confirmed that report. This project includes a more thorough examination, both theoretical and practical, of solutions for the sorting of copper and stainless steel.

The investigation demonstrated a practical way of separating these two metals based on their electrical conductivity. The equipment used for the separation was based on eddy current separator theory. This separator was selected as the final solution to sort copper from stainless steel. Results of research conducted in the laboratories of Russia and China have been carefully analysed and corresponding conclusions have been made.

Part of the project's research included a market analysis and a description of some commercially available systems is also presented in this thesis. As a result the solution described in this thesis can be used in any factory where stainless steel and copper are the waste products.

Keywords

separator, copper and steel separation, eddy current separator, metal separation

Confidentiality

CONTENTS

1 INTRODUCTION

The company Danfoss set a goal to find a solution for sorting scrap of metal. The task was to find a market ready solution or possible new solutions for separation of waste. As a result detailed report was provided to Danfoss as well as possible solution. It was background for writing this thesis.

This thesis will discuss the properties of copper and stainless steel, on the basis of these properties will be selected the possible methods of separation those two metals from each other. At the beginning of the thesis special attention to the importance of recycling will be paid as well as will be mentioned both economic and ethical aspects of the issue. The areas of use both metals will be considered too.

This thesis will be closely examined the theory which is behind the equipment called the eddy current separator. This separator has been selected as a final solution to sort copper from stainless steel. The results of experiments carried out in the laboratories in Russia and China will be examined also.

During research work the market analysis was conducted and description of some commercially available systems are also given in this thesis.

As a result the solution provided here can be applied to any plant where waste products are copper and stainless steel.

2 PROBLEM DESCRIPTION

The purpose of the original project was the search for solution of separation metal waste produced as the result of manufacturing of heat exchangers on Danfoss factory. The material flow from punching process on Danfoss factory was stainless steel AISI 304, stainless steel AISI 316 and brazing copper. Brazing copper is considered as pure copper with no additions. Amount of flow in 2008 have been the following: stainless steel AISI 304 mixed with copper - 15 tons, stainless steel AISI 316 mixed with copper – 43 tons, totally 58 tons. In previous 2006 the flow was the following: stainless steel AISI 304 mixed with copper – 45,8 tons, stainless steel AISI 316 mixed with copper – 8,3 tons, totally 54,1 tons. This information was provided by Danfoss [1].

Because copper thickness is much lower than steel, there is more steel than copper in weight percentage [2]. In quantitative meaning the output of stainless steel and copper is the same. In punching there come always exactly the same amount of both. The task was to separate the copper from stainless steel waste. Although the two types of steel have been used but in general both are similar in properties, so separation from each other was not required.

2.1 Why the Separation is Needed?

There is a resonable question about the reason for which is necessary to make such a separation of metals. Why do we need separation of metals and sorting of waste? Although the primarily matter for any company is getting more profit it would still first to draw attention to environmental concerns. If we constantly talk about it maybe even more people and even more countries are thinking about caring of the environment. Therefore it is needed to pay special attention to issues of recycling in this thesis.

2.2 Recycling

What is recycling? It is the process of collecting used materials which is usually considered as waste and reprocessing them. [3] Recycling is not the same as reuse. Re-use usually just means using old products again, may be after repairing. But recycling means using the core elements of an old product as raw material to manufacture new goods.

The recycling process can be divided into three stages. In the first stage the recycling metals are collected, cleaned and made ready for the process of recycling. The second stage is to process the old metals into new products. It is the main step of the total process. The third stage is to place it in the market so that people can buy these products. The more people buy these products the more we can save our nature and our resources. By this process we can save our environment.

It is very important to recycle metal. Scrap metal does not mean garbage. It is a kind of metal that can be recycled easily and use it in other way. It is very important to reuse our available resources than wasting the resources of the nature. By recycling the metal and other things we can save the nature in a smart way. We must recycle the metal when it is much easier to do this. It is possible and easy to recycle all kinds of metals we have on this earth. Copper and stainless are valuable today. Copper is very expensive. A kilogram of copper has good value and it does not matter either the copper is burned or not. We can recycle it in a very easy way and so we do not need to get copper from the mines and harm the nature. Stainless steel is also very valuable today, it is costlier than iron. The values of these metals changes as the market changes.

Let's discuss more about stainless steel. Stainless steel is 100% recyclable. In fact, over 50% of new stainless steel is made from remelted scrap metal, rendering it an eco-friendly material. [4] As well as iron, stainless steel contains other valuable raw materials, especially chromium, nickel and molybdenum, which makes recycling stainless steel economically viable.

Like all the metallic materials stainless steel is also produced in the same way. Stainless steel is an alloy of iron. Coke, iron ore and limestone is used to produce stainless steel. The stainless steel is produced in two ways. One is called the basic oxygen furnace (BOF) process. The second process in known as the electric arc furnace (EAF) process. 25 to 35 percent recovered steel is used to make this new steel. Molten iron from blast furnaces is combined with pure oxygen which causes a chemical reaction. Stainless steel is used in many ways. It is used in many industrial machines and other products. BOF steel is very need in making these things to as it flatten into sheets. On the other hand the EAF steel is made by 100 percent recover steel. Scraped steel is melted and refined after an electric current goes from those materials. Beams, steel plates and other products are made by this kind of steel. [5]

Recycling and production is a part of the life cycle of these metals. It is also very much cheaper to recycle steel than to get in from the mines. It is both costlier and harmful for the nature and environment. It saves the environment from the green house gases too as manufacturing these steel produces less green house gases.

One source says: "In 2006, about 28 million tonnes of stainless steel were produced". [6] The same source indicate that to make it, about 17 million tonnes of recycled stainless steel and other recycled ferrous materials were used. According to the same source any stainless steel object has an average recycled content of about 60%. The Figure 1 shows the percentage of recycled steel in the new product.

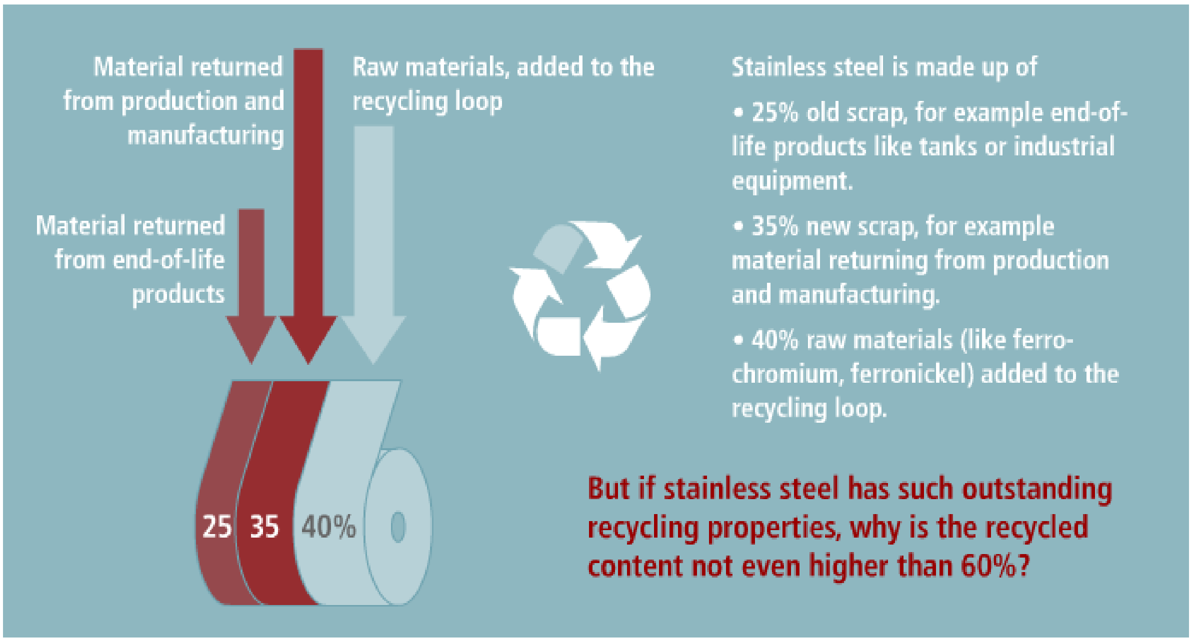

Figure 1. Content of recycled steel in the new product. [6]

The author of illustration asks the question: "But if stainless steel has such outstanding recycling properties, why is the recycled content not even higher than 60%?" The answer is easy. The stainless steel that recycles today may have been put into the market 20-30 years ago, but production today was grown a lot. So it is not enough material for recycling to cover all the needs. The recycled content is only limited by how much stainless steel was put into the recycling few years ago. The unparalleled growth of stainless steel production and use explains why, in 2006, 11 million tonnes of virgin material was added into recycling loop along with the 17 million tonnes of recycled material.

Thus, we must understand that stainless steel is not spent, it remains a part of a closed system. In contrast to many other materials stainless steel can be recycled without any degradation! Recycling of stainless steel protect our natural resources.

Now if we talk about copper. Copper can be provided in the environment both by human and nature. Natural sources are windblown dust, decaying vegetation, forest fires and sea spray. At the time of refining and mining of copper sulphur dioxide is produced which has a harmful effect on the environment and it spoils the environment in many ways. But these losses can be minimized by using the sulphur dioxide to produce sulphuric acid. But when the copper is used for recycling these harmful gases are emitted.

As copper is produced both naturally and by human it is very much widespread in the environment. Copper is commonly found in the industrial settings, near mines and other places. Rivers are deposing sludge in the banks of the river which contains copper. It happens as we throw wastes in the rivers containing copper. Coppers are found in the air as we burn many things made of copper and other fuel fossils. Copper is also found in the rain water. The copper is found in a huge quantity in the soil. The copper is very much harmful for the environment. Water soluble copper harms the environment in a very bad way. It harms a lot in the case of agriculture.

Copper disturbs the activity of the soil and has a very harmful effect on the soil. The productions of agriculture slow down for this reason. The animals are also disturbed for this poisoning of copper. Sheep suffer a lot for this copper poisoning. It is very much harmful for the animals. It is badly needed to stop the copper poisoning.

Landfill is a good option for waste disposal. When the copper and other copper made objects are dumped in the ground is known as landfill. The main problem is copper does not breaks out in the environment and it harms and plants and animals a lot when it gets mixed with soil. It is very hard for a plant to survive with the copper mixed soil. So we can rarely find plants near the places where copper is used. So it is very important to keep the cultivatable lands free from copper to get good and fresh plants and vegetables. Recycling the copper can save the environment and the costs of landfill too.

In order to get copper from the mine and extract the copper from the copper ore lots of energy is needed. This wastes a lot of energy and money. 100 GJ/tonne of energy is needed to extract copper from the copper ore. On the other hand 10 GJ/tonne of energy is needed in order to recycle the copper. This saves the waste of oil, gas and coal. It also reduces the production of carbon dioxide gas.

Copper is a very useful metal today. It is very much cheaper to recycle the copper than extracting the copper from mines. It saves almost 90% of the total cost. It is very much profitable to recycle the copper than extracting it from the mines. [7]

In order to summarise the total thing and describe the profit of recycling the following benefits are given below [3] :

Saves energy. It is cheaper to recycle metal to produce a new metal made product. It saves a lot of energy and other costing too. Producing metal made products from the virgin ore wastes a lot of energy. It also wastes some energy to transfer the raw material from the mine to the right place. In order to keep the environment neat and clean and save the energy it is important to recycle metals to produce metal made products.

Saves the environment and natural resources, reduces pollution. By recycling the metals we can reduce the emission of carbon dioxide gas in our environment. Thus we can save our nature from air pollution and other pollutions. Recycling the metal saves a lot of energy as it is not a tough process. But using virgin ore wastes a lot of energy. Recycling metals also help to decrease the amount of green house gas from the environment. In the process of manufacturing the virgin ore it produces dangerous and toxic gases like sulphur dioxide, methane and carbon dioxide which spoils the normal environment of the nature. To use the virgin ore we need to use more coals, fuel and gasoline which are a waste and harmful for the nature. Less water is used and less water is polluted when we recycle metal on the other hand using the virgin ore is a waste of energy and money and harmful for the environment.

Saves space for waste disposal. Maximum landfill sites are today filled with a huge quantity of waste products. Some of those are non-biodegradable that will take a long time to decompose. Recycling the waste products can help to get more spaces in the landfill sites to throw waste products.

Economic benefits. As recycling metal saves energy and the nature, it also saves the money too. We can save our money in various ways by recycling waste products and using the products which is made of recycled products. Using the virgin metal in order to make new products wastes our money. Taking the virgin ore from mines, processing the virgin ore, transporting the metal and other things are very expensive. On the other hand recycling waste products and producing new products can save a lot of money.

Recycling metals creates an opportunity for many people to get employment. Recycling business is a very profitable business today. It needs a small investment for this business but this business can give you a lot of benefits at the end. Recycling cans, plastic products and metal products and producing new products from those waste products can help you to earn a lot of bucks. In this modern age of science and technology recycling products has opened a new era. There are lots of economical benefits for this.

This is very commendable that to care about the environment give much attention here in Finland. Like in other civilized Europe here we do sorting garbage, we don't use hazardous materials (for example, prohibited by RoHS directive), we do recycling and we are trying to comply with other EU normatives. All that protects the environment from destruction.

2.3 Economic Benefits for Manufacturer

The manufacturer sells the waste to the companies involved in its recycling. It is not a secret that the price of copper is higher than the price of stainless steel. If waste is not separated the price per ton of scrap is less. It is easy to understand why manufacturer may want to separate scrap before sell it for recycling. The company Danfoss has been provided information regarding the economic benefits [1]. This information was collected into the Table 1.

Table 1. Economic benefits example.

Metal scrap	**Volume in 2006, tons**	**For recycling, tons**	**Supposed volume, tons**	**Price 1.4.07, euro/tn**	**Income, euro**
Mix AISI 304 + Copper	61,9	45,8		1868	53410
Mix AISI 316 + Copper	11,2	8,3		1166	15482
Total		54,1			68892
AISI 304			6,63	3862	25606,61
AISI 316			36,64	2495	91428,77
Copper			10,82	4500	48684,60
Total					165719,98

With approximation that from total amount of copper and stainless steel scrap 74% are suitable for recycling and from weight of scrap 20% is copper and 80% is stainless steel they have calculated that with current prices (year 2007) if they sell out mixed copper and stainless steel money will be get about 68900 euro and if they are separated they get about 165700 euro which is mean difference in 96800 euro in a year [2].

2.4 Where to Use?

As noted earlier, the first study was conducted for Danfoss. The company produces heating systems (radiators) by punching with use of stainless steel and copper and so the output is a scrap of these metals. The Figure 2 shows this waste. However, information from this thesis can apply to any process in which the output is a waste in the form of copper and steel.

Figure 2. Metal scrap after punching process.

Danfoss is one of the largest industrial companies with head office in Denmark. The company has 79 factories in 22 countries, 110 sales companies and more than 400 agents and distributors all over the world. [8]

Danfoss operates globally as one of the leading supplier of compressors, automated solutions to the refrigeration and air conditioning industry as well as heating systems. The Danfoss product range is used within a number of business areas, such as household-, commercial-, food retail and industrial refrigeration as well as air conditioning, products for the wholesale refrigeration market and automation in various specific industrial sectors and a wide range of components and solutions for generation, distribution and use of heat.

As stated on the company website: "Danfoss seeks to obtain its goals with a minimal consumption of raw materials and energy, the least possible impact on its surroundings and the most efficient use of resources. Danfoss has a long tradition for a social responsibility towards both employees and the surrounding environment." [8]

2.5 Problem Localization

In fact, the problem of sorting is divided into two problems. As a result of stamping two materials are connected together because of curling its edges (see Fig. 3). Thus, we must first solve the problem of separation of particles from each other. The second problem is the actual problem of separation one metal from another, so copper from stainless steel. In order to find the appropriate way of sorting and separation of copper from stainless steel it is necessary to compare the different properties of these materials. This will be done in the next section.

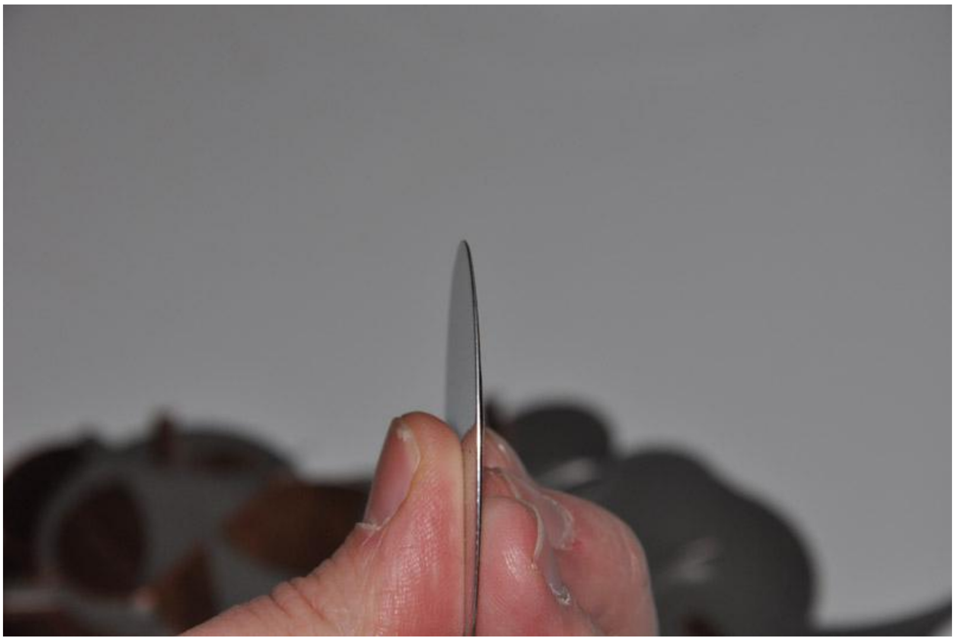

Figure 3. Curling edges.

3 METAL COMPARATION

In order to find the appropriate way of sorting and separation of copper from stainless steel, it is necessary to compare the different properties of these materials. It is also possible to analyze simensions and shape. When we know the properties of both materials, we can choose the one characteristic that most distinguishes one material from another. Next we will try to find a way to separate these two metals based on the difference in this property. It should be noted that this would help solve a problem of separation of copper from stainless steel, but will not solve the problem of mechanical separation of metals from each other. Chapter 6 of this thesis will be devoted to the mechanical separation issue.

The areas of use both metals should be mentioned. Why do it? This will help us to understand at what other industries they are used and where else a solution from this thesis can be applied for separation such a metals. To start a briefly look at the shape and dimensions of the source material.

3.1 Shape and Dimensions of Source Material

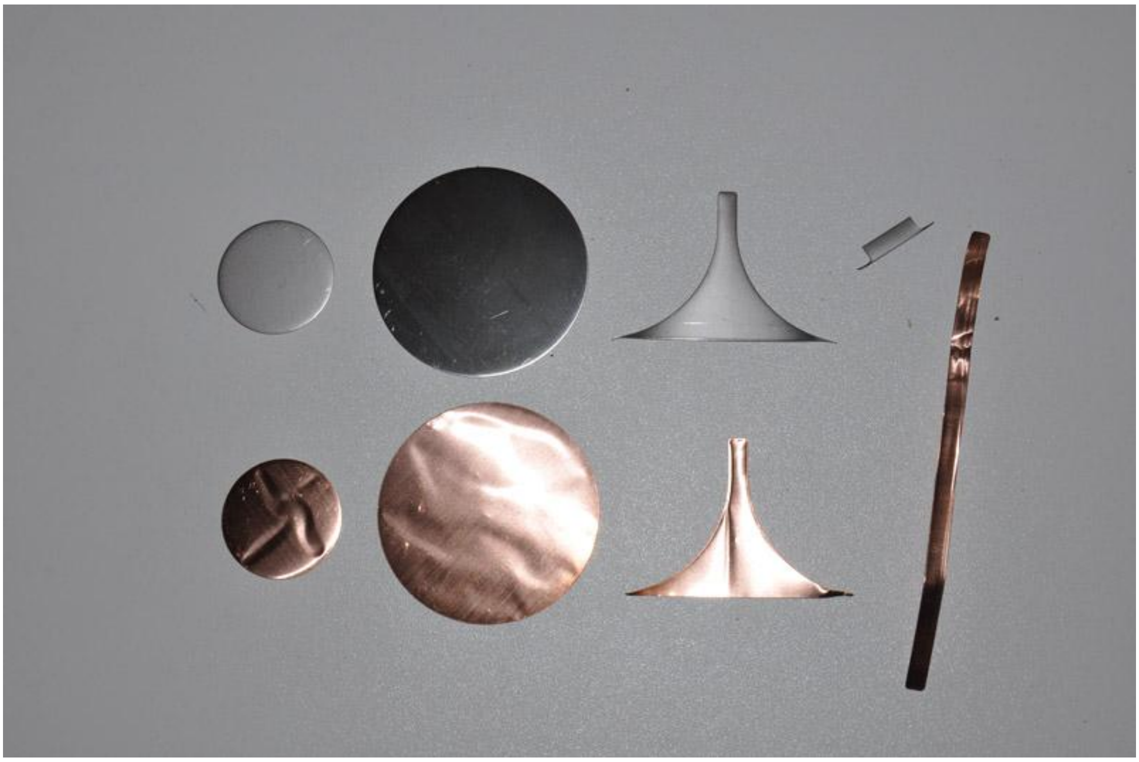

Figure 4. Shapes of source material.

In the case of Danfoss we have a pieces of copper and stainless steel of different shape and size at the output (see Fig. 4). We have circles of different sizes, different rectangles (strips), and other complex shapes. Dimensions of pieces are the following. Round pieces with diameter 20-70mm, other shape pieces with dimensions about 5x100mm, etc. Thickness of copper is 0.1mm and thickness of stainless steel is 0.4mm. Thus, we have different sizes and shapes. However, we can not use the difference in the form of materials for their separation from each other. This is because we have a pair of pieces. As copper and stainless steel output is obtained in the same amount - every piece of stainless steel corresponds to the same piece of copper.

3.2 Copper Properties

Copper is a reddish metal with a shiny (reflective) outlook and a cubic crystalline structure. It is very easy to recognise copper by the colour. Copper reflects red and orange colour lights and also absorbs frequencies in the visible spectrum for its band structure. That is why it has a nice reddish colour.

Copper is one of the most electrical conductive metals. It has good thermal conductivity, corrosion resistance, ease of forming, and ease of joining and so on. Iron is harder than copper but zinc is softer than it. Copper can be polished easily to give it a brighter look. Copper is less chemical reactive, it only turns into a greenish surface in the moist air which is called the patina. Patina can protect this metal from destructions and other dangers. We can apply varnish coatings on copper to retain its colour and quality. We can also add acrylic coating with benzotriazole to last it for a long time.

After iron and aluminium copper is the mostly used metal in the world today. [3] It is mainly used in electrical products and plumbing. It is the best metal for wiring for its high electrical conductivity. It can be drawn into fine wire. It is also used a heat exchangers as it is a good heat conductor.

Copper has a very low strength/weight ratio. It is a dense cladding material but a poor structural material. Copper and its alloys are found in rod, plate, strip, sheet, tube shapes, forgings, wire, and castings. These kinds of metals are grouped in composition in different categories such as coppers, high-copper alloys, brasses, leaded brasses, bronzes, aluminium bronzes, silicon bronzes and copper nickel.

The mostly used copper is C11000 for its high electrical conductivity. Sometimes the name "tough pitch" is used for this type of copper. [9] It contains almost 0.03% of oxygen and a minimum of 99.0% copper. C10100 and C10200 is oxygen free. It gives immunity to embitterment in high temperature. Adding phosphorus produces grade C12200 copper which is called the water-tube copper. Cadmium increases the strength of the copper to 50% but it loses the conductivity to 85%. A little amount of cadmium increases the softening temperature. Adding Tellurium or sulphur in a little amount in Grades C14500 and C14700 increase the mechanical ability. When the material is cold worked or hardened, it becomes less ductile. Its yield strength approaches tensile strength.

Table 2. Copper properties.

Properties	**Value**
Yield Strength	70 MPa (10.2 10^3psi)
Tensile Strength	220 MPa (31.9 10^3psi)
Modulus of elasticity	117 GPa (17 10^6psi)
Specific Heat Capacity	385 J/kg-K (0.092 BTU/lb-°F)
Thermal Conductivity	391 W/m-K (2710 BTU-in/hr-ft^2-°F)
Thermal Expansion	16.9 10^{-6}/°C (9.39 10^{-6}/°F)
Density	8910 kg/m^3 (556 lb/ft^3)
Electrical Conductivity	100 % IACS
Electrical Resistivity	17.2 nΩ-m

In our case it was not specify what alloy is used. However, it was stated that the composition of the alloy 99% copper [1]. But as we learned above even 1% of some other materials included in copper alloy can greatly reduce the conductivity of the alloy. There is no intend to have a high electrical conductivity on Danfoss when they manufacture heating radiators. They require a high thermal conductivity, but not electrical conductivity. Therefore we can not be sure that the copper used there has high electrical conductivity. For us it is very important to know what the electrical conductivity of the alloy. Why is this so important? Later will be clear that based on this property will be chosen the way of separation of metals.

The Table 2 shows the main properties of copper. Properties given for UNS C11000 copper, which is the most common grade, and also the basis of the % IACS (International Annealed Copper Standard) measurement system for electrical conductivity. Properties were taken from ASTM B3 Standard. [10]

3.3 Stainless Steel Properties

Stainless steel is an iron based metal which contains at least 10% of chromium. It is silver coloured and very reflective. Chromium saves it from oxygen and moisture. Chromium saves the iron from being red coloured and other dangers. It has a slim layer on the iron which is very shiny. For this quality it is called the stainless steel. The main purpose of the stainless steel is to protect from rust, stain, moisture and other things. It hardens the material and gives it a good longevity. It is a good resistor against adverse atmospheric conditions such as carbon dioxide, moisture, electrical fields, sulphur, and salt, and chloride compounds, ozone, extremes of weather. [4]

There are over 150 grades of stainless steel, of which fifteen are most common. The American Iron and Steel Institute (AISI) defines grades. At Danfoss for heat radiators production stainless steel AISI 304 and stainless steel AISI 316 are used.

Type 304 stainless steel is a under the T 300 series. It has approximately 18% chromium and 8% nickel, with a maximum of 0.08% carbon. It is called the Chromium-Nickel austenitic alloy. It has good corrosion resistance and can be used in different situations but it is not useable in the salt water. T-304 stainless steel is the most used stainless steel in the world today. [12] It is found in our most accessories in the kitchen and other places. Knives, pans and other cookeries are made by this T-304 steel. It is always used in the pipelines and many other things of construction. Type 304 is used in all the handling, crushing, and hauling equipment.

Type 316L stainless steel is molybdenum bearing austenitic. It is more resistant to general corrosion and pitting than conventional nickel chromium stainless steels Type 304. According to the Product Data Bulletin published by AK Steel Corporation typical uses for this type of stainless steel include exhaust manifolds, furnace parts, heat exchangers, jet engine parts, pharmaceutical and photographic equipment, valve and pump trim, chemical equipment, digesters, tanks, evaporators, pulp, paper and textile processing equipment, parts exposed to marine atmospheres and tubing. [11] Type 316L is used extensively for weldments where its immunity to carbide precipitation due to welding assures optimum corrosion resistance.

Table 3. Stainless steel properties.

Properties	**Value**
Yield Strength	260 MPa (37.7 10^3psi)
Tensile Strength	570 MPa (82.7 10^3psi)
Modulus of elasticity	193 GPa (28 10^6psi)
Specific Heat Capacity	500 J/kg-K (0.12 BTU/lb-°F)
Thermal Conductivity	16.3 W/m-K (113 BTU-in/hr-ft^2-°F)
Thermal Expansion	15.9 10^{-6}/°C (8.83 10^{-6}/°F)
Density	8030 kg/m^3 (501 lb/ft^3)
Electrical Conductivity	2.33 % IACS
Electrical Resistivity	740 nΩ-m

There are not so much differences between AISI 304 and 316. For example, due to the higher nickel content, AISI 316 grades works harden at a lower rate than AISI

304. There are many industrial processes that require a higher level of resistance to corrosion than AISI 304 can offer and therefore AISI 316 is the answer. We can say that except for corrosion resistance, properties are similar to 304.

Thus, the differences between these types of stainless steel are irrelevant if we consider the application of it in practice. Use these differences to separate the metals from each other is a difficult task. But since the task is not to separate one stainless steel from another it will not be considered the small differences in properties between these two types of steel.

The Table 3 shows the basic properties of stainless steel. Properties given for Type 316 (also called "Marine Grade" or "18/10"). Data for this material was obtained from ASTM A666 Standard [13], ASTM A240 Standard [14].

3.4 Difference in Properties & Separation Possibilities Based on Properties

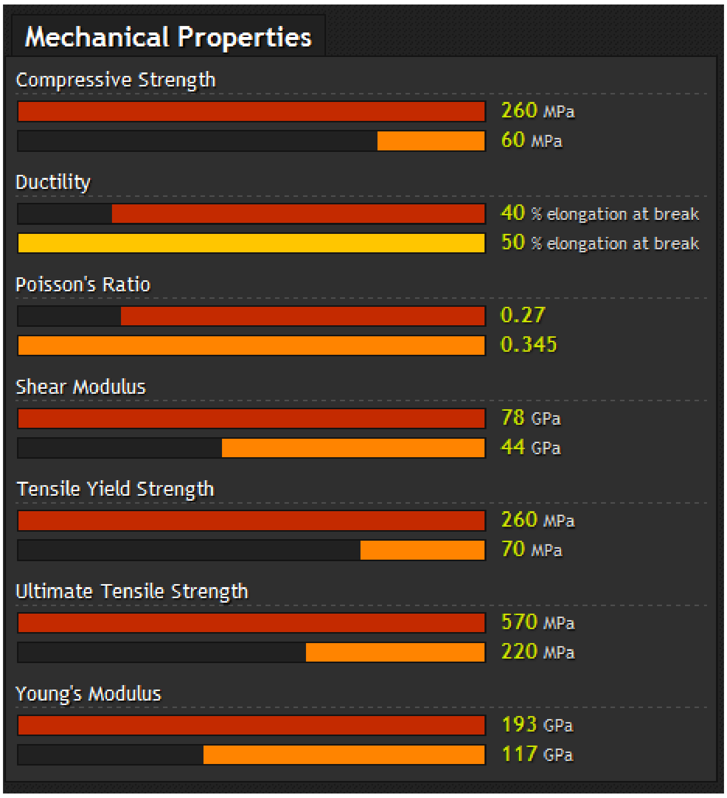

Figure 5. Difference in mechanical properties of electronic copper and marine grade stainless steel. [15]

The website MakeItFrom.com can use a handy tool for comparing the properties of the two materials. Comparison was made for electronic copper and marine grade stainless steel. The results can be seen on the two charts (Fig. 5, 6). Stainless steel are first lines (red), copper – second lines (yellow). A brief review of two metals, as well as referring to this chart shows what properties of these metals can be used to separate them from each other.

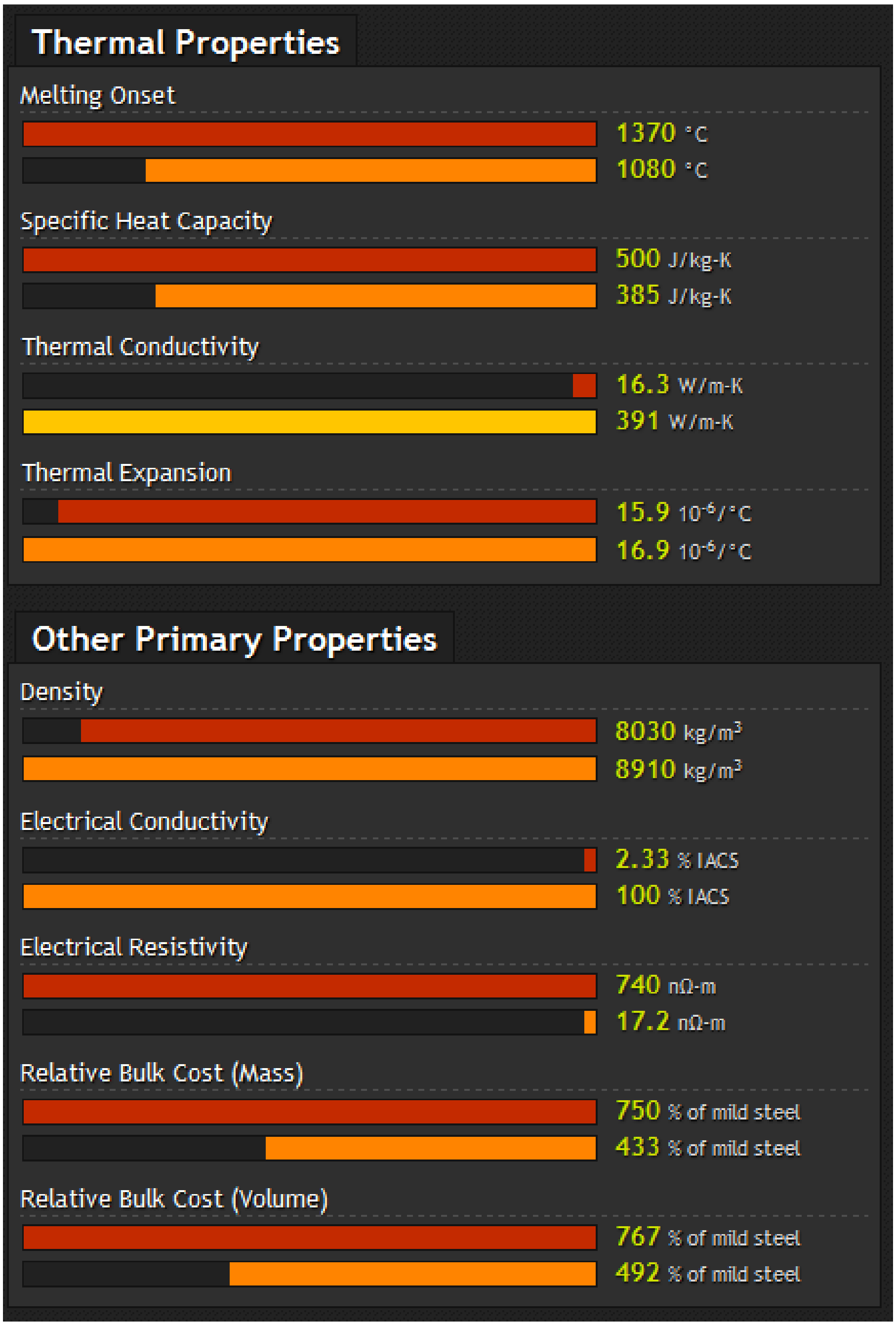

Figure 6. Difference in thermal and other primary properties of electronic copper and marine grade stainless steel. [15]

It is hardly possible to find an acceptable way of separating metals on the basis of their mechanical properties (hardness, tensile strength, elongation at break, modulus of elasticity, etc.). Thus, there is no reason to pay much attention to such properties.

Both metals are nonferrous. That is why they do not have the express magnetic properties. So we can not use an obvious way to separate using a magnet. The differences in the density of materials are negligible, so use this property for the separation also seems inpossible. The difficulty is also the form of waste. Waste in the form of thin flat plates is difficult to assign to the sorting conveyor. If the wastes were in the form of pebbles, they would have been easy to spread out on the conveyor. It can not be said so about the waste in the form of plates. Thermal Conductivity varies greatly, but it's hard to imagine how it can be used for the separation of metals. At least in this thesis, the issue is not covered.

It is obvious that the color of metal - one of the most striking differences. With regard to the differences of colors we have no questions. It is clear that these two metals vary greatly in color and this property can be used to try to separate. So, first of all we pay attention to the difference in colors. Sure, there must be a system that can recognize the material on its color. Investigation of this matter will be dealt with in the Chapter 5 of this thesis.

However a property requires more careful consideration is the electrical conductivity or its inverse property - electrical resistance. As can be seen in the diagram, these metals are very different in the electrical conductivity. It will be paid more attention to this property and then it becomes clear why it was done.

3.5 Electrical Conductivity of Copper and Stainless Steel

In order to begin it is needed to recall the physics with regard to electricity. It is known to all that the electron is one of the elements of an atom. Electrons are found around the nucleus of an atom. The electrons have negative electrostatic charge. During the nuclear reaction it can move from one atom to another. The directions that the electrons use to move have no bounding unless it is forced to move to an individual direction. This movement of electrons by some force in particular direction is known as electrical current. The force that makes an electron to move in an individual direction is called the electromotive force or E.M.F. Battery is one of the sources of the E.M.F. On the other hand resistance give the electrons a break to move forward. The materials that have a low resistance are known as the conductor. [16]

The property of a metal that measures its ability to conduct electricity is called electrical conductivity of metal and it shows how easily electrons move through that metal. Metals usually have a good electrical conductivity as the electrons can move very easily. They have a definite property of sharing electrons. [17]

The highest electrical conductivity occurs in metals that have only one electron occupying a state in a shell of an atom. Gold, silver and copper are the metals having good electric conductivity. Metals are usually found in the left side of the periodic table. Some electrical conductive metals are made of two or more metals. They are brass, bronze, steel and others.

Table 4. Conductivity of copper and steel alloys based on information published by Eddy Current Technology Incorporated

Material	Resistivity, ohm-m	Conductivity, Siemens/m	% IACS
Copper, Pure	1.664E-08	6.009E+07	103.60
Copper, Electrolytic Tough Pitch (Annealed)	1.707E-08	5.858E+07	101.00
Copper, Deoxidized (Annealed)	2.028E-08	4.930E+07	85.00
Steel, 304 Stainless	6.897E-07	1.450E+06	2.50
Steel, 316 Stainless	7.496E-07	1.334E+06	2.30

Electrical conductivity expressed as a percent of the International Annealed Copper Standard (% IACS), which is $58x10^6$ S/m ("S" is Siemens). Siemens is a unit of electrical conductance equal to one ampere per volt (named from Werner von Siemens). Siemens is the unit of measure for electrical conductivity used by the International System of Units (SI). Another term for siemens is mho (which is ohm spelled backwards). In fact, siemens = 1/ohm. As it was mentioned before in UNS C11000 copper is the basis of the % IACS measurement system for electrical conductivity.

Electrical conductivity is the inverse of electrical resistivity and conductivity is typically calculated from resistivity. If resistivity is known, conductivity provides no additional information, and is merely displayed for convenience in different documentations.

Electrical resistivity is a magnitude of resistance to the passage of electricity. Uses units of electrical impedance times distance. Since the difference between an electrical conductor and insulator can be as much as 20 orders of magnitude, resistivity is often given simply as 10^x. Also called "Volume Resistivity", and is not to be confused with "Surface Resistivity".

Table 5. Resistivity of copper. [19]

Bibliographic Entry	**Result (w/surrounding text)**	**Standardized Result**
Cutnell, John & Johnson, Kenneth. *Physics 4th edition.* New York: Wiley. 1998: 755.	"Table 20.1 Resistivities of Various Metals Copper 1.72×10^{-8}"	17.2 nΩm
Yasunari Maekawa, Hiroshi Koshikawa and Masaru Yoshida. Anisotropically conducting films consisting of sub-micron copper wires in the ion track membranes of poly(ethylene terephthalate). *Polymer*. Volume 45, Issue 7 (1 March 2004): 2291-2295.	"resistance (R_t, Omega/cm^2) is derived from the following equations (1) R_t = 1/S = rho L/(pi (r/2)^2 F) where rho is copper resistivity (1.67×10^{-6} Omega cm), L is wire length (3.6×10^{-3} cm), r is cross-sectional diameter of copper wires …."	16.7 nΩm
Copper [Cu]. allmeasures. 1999-2004.	Electrical Resistivity (rho)0.0000000168 ohm.m	16.8 nΩm

From the table "Conductivity of metals sorted by resistivity" published by Eddy Current Technology Incorporated could be obtained the following data for copper and stainless steel alloys (see Table 4). [18]

There are tables which state the testing result of electrical resistance for different metals collected from various sources on website Hypertextbook in the section The Physics Factbook with header An Encyclopedia of Scientific Essays Edited by Glenn Elert Written by his students. [19] The information from these tables was processed and presented in the Table 5 and Table 6.

Table 6. Resistivity of steel. [19]

Bibliographic Entry	**Result (w/surrounding text)**	**Standardized Result**
C. Weast, Robert. *Handbook of Chemistry and of Physics- 48th Edition.* Ohio: The Chemical Rubber Co., 1968: F-130.	"Steel, piano wire (0 °C): Resistivity = 11.8×10^{-6} Ωcm"	1.18×10^{-7} Ωm
Resistance and Resistivity. School Science.	"Steel (varies): 10 to 100×10^{-8} Ωm"	1 to 10×10^{-7} Ωm

As a result, it is clear that the values of electrical conductivity of stainless steel and copper given in ASTM standards are in the range confirmed by other experiments.

After a detailed review of this property it became clear that the electrical conductivity of copper is really very different from the electrical conductivity of stainless steel. It is known that there are separators for the separation of plastic waste from the metal. It has been suggested that steel can behave like plastic (so to be as a non-conducting material), and copper will act as a metal (conductive material) if use such equipment for separation. It was therefore decided to test this method of separation. This issue will be disclosed in detail in the next section of thesis.

4 EDDY CURRENT SEPARATOR

In Section 3 we remember the foundations of physics in respect of electricity and discussed the concepts of resistance and electrical conductivity of metals. It will be considered a theory that underlies the work of the eddy current separator - Eddy current theory. Eddy current theory is based on electromagnetic induction, which will be described below. Theory of eddy current separator will also be discussed in this section.

4.1 Electromagnetic Induction and Faradays's Law

In 1830 Joseph Henry and Michel Faraday founded that a variable magnetic field can induce an electric current on a conductor even if this conductor is separate to the source of the magnetic field. But before that in 1824 Oersted discovered that current passing though a coil generates a magnetic field that is capable of shifting the compass needle. Thus, these scientists found two opposite effects, which are part of the one theory. Electromagnetic induction is the process of generating electrical current in a conductor by placing the conductor in a changing magnetic field. It is called induction because magnetic field induce the current in the conductor.

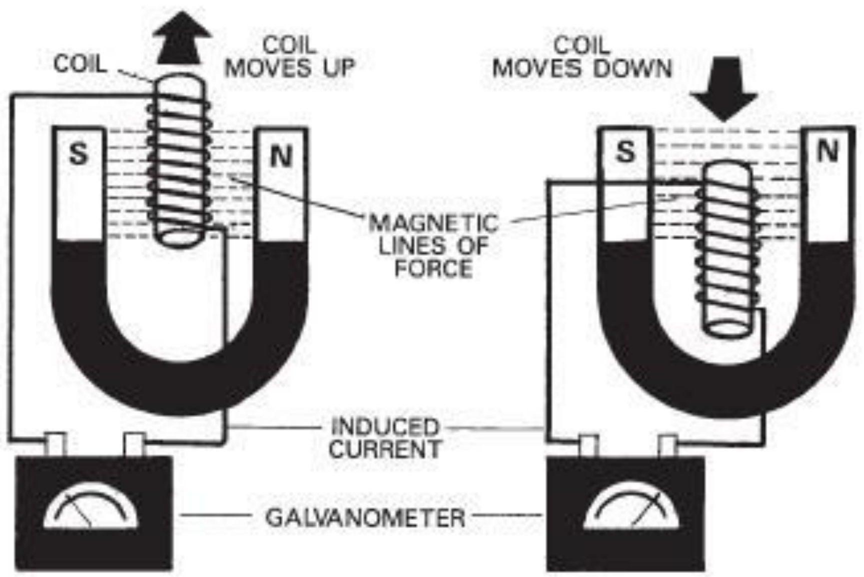

Figure 7. The illustrate of electromagnetic induction, Faradays's Law. [19]

Faraday's Law of induction says that any change in the magnetic environment of a coil of wire will cause a voltage (electromagnetic force, or EMF) to be induced in the coil.

Faraday also noticed that the rate of change of magnetic flux affects to the amount of induced voltage. Another read for the Faraday's Law for a straight conductor is EMF of electromagnetic induction in the circuit is numerically equal and opposite to the rate of change of magnetic flux through the surface bounded by this contour. [21]

This formula (1) shows Faraday's Law for a straight wire:

$$\mathcal{E} = -\frac{d\Phi}{dt}, \quad (1)$$

where $\mathcal{E}$ is the EMF and $d\Phi/dt$ is the rate of change of magnetic flux in webers/second.

Induction reflects dependence on the rate of change of the magnetic field. It is measured in unit of Henries (H)**.** One Henry is the amount of inductance that is required to generate one volt of induced voltage when the current is changing at the rate of one ampere per second.

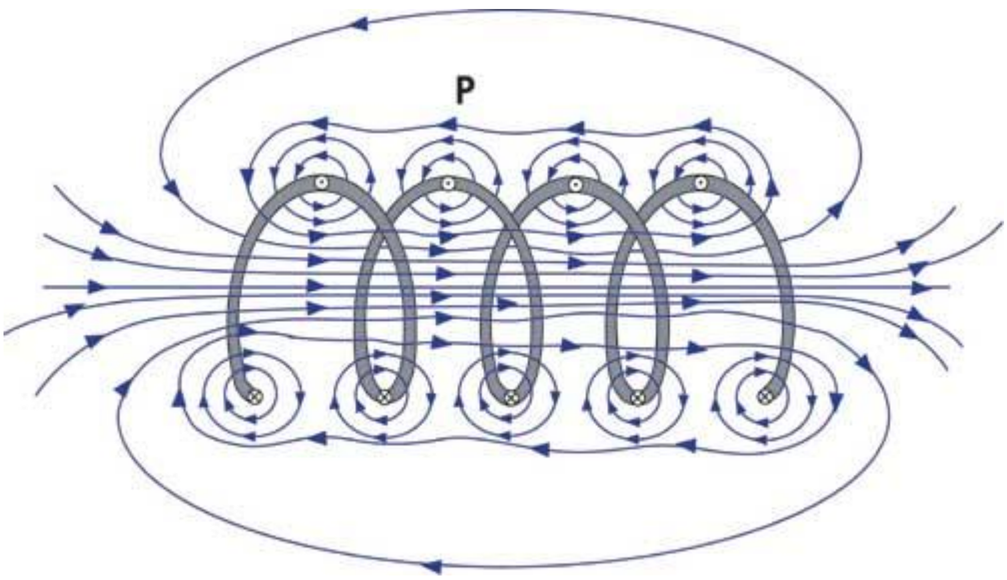

Figure 7. Mutual-inductance. [16]

When induction occurs in an electrical circuit and affects the flow of electricity it is called inductance. Self-inductance (sometimes just inductance) is the property of a circuit whereby a change in current causes a change in voltage in the same circuit. Mutual-inductance is the effect when one circuit induces current flow in a second nearby circuit (Fig. 7).

The number of turns in the coil will have an affect on the amount of voltage induced into the circuit. By researching this phenomena Faraday modified the Law and for a coil it must be the following:

$$V_L = N \frac{d\Phi}{dt} , \tag{2}$$

where V_L is induced voltage in volts, N is a number of turns in the coil and *dΦ/dt* is a rate of change of magnetic flux in webers/second.

The equation (2) states that the amount of induced voltage (V_L) is proportional to the number of turns in the coil and the rate of change of the magnetic flux (*dΦ/dt*). In other words, amount of induced voltage will be increased together with increasing of intensivity of the flux and number of turns in the coil.

It is much easier to measure current than magnetic flux in a circuit, so the next equation can be used to determine the induced voltage when frequency of the current or inductance are known. This equation can also be reorganized (3) to allow the inductance to be calculated when the amount of inducted voltage can be determined and the current frequency is known:

$$V_L = L \frac{di}{dt} , \tag{3}$$

where V_L is induced voltage in volts, L is the value of inductance in henries and di/dt is a rate of change of change of current in amperes per second. [20]

4.2 Lenz's Law

In 1834, Heinrich Lenz stated the principle for determining the direction of the induced current in a loop. Moves the magnet through the coil wire induces the current in the wire. But it doesn't stop there. That current then generates its own magnetic field. That secondary induced magnetic field opposes the initial field – the field from move a magnet. This is Lens's Law.

Lenz's Law states that the magnetic field of induced current is oppose to the change in magnetic flux that caused this current. [22] This means, in practice, the **eddy currents** communicate with the test coil by developing secondary flux that cancels a portion of the coil's flux equivalent to the magnitude and phase of the flux developed by the eddy currents. [20] Lenz's law is important in understanding the property of inductive reactance, which is one of the properties measured in eddy current testing.

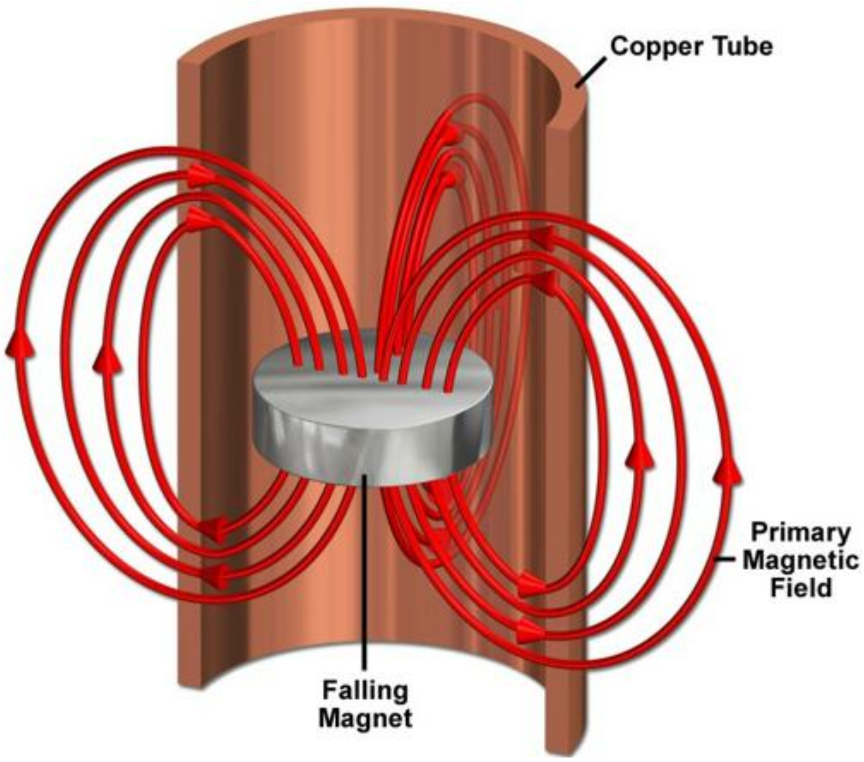

Figure 8. Permanent magnet falling through the copper tube. [23]

The first person who really discovered eddy current was the French physicist Léon Foucault (1819-1868). That is why eddy currents also called **Foucault current**. In

September, 1855, he discovered that the force required for the rotation of a copper disc becomes greater when it is made to rotate with its rim between the poles of a magnet, the disc at the same time becoming heated by the eddy current induced in the metal.

One good illustration could be used to show, how eddy current and Lenz's Law works in practice. It could be illustrated by dropping a rare-earth or cow magnet through tubes that have inside diameters slightly larger than the magnet itself. The magnet will fall freely through a 90-cm PVC tube but will fall slowly through a copper or aluminium pipe of the same length. You could see this explanation on the pictures above (Fig. 8).

Permanent magnet has its own field (Primary Magnetic Field, Fig. 8). As the magnet falls, its field is constantly changing position. When it passes through a given portion of the copper pipe, this portion of the tube experiences a changing magnetic field which induces the flow of eddy currents in the conducting material (Fig. 9). They called so, because they circulate as eddies in water.

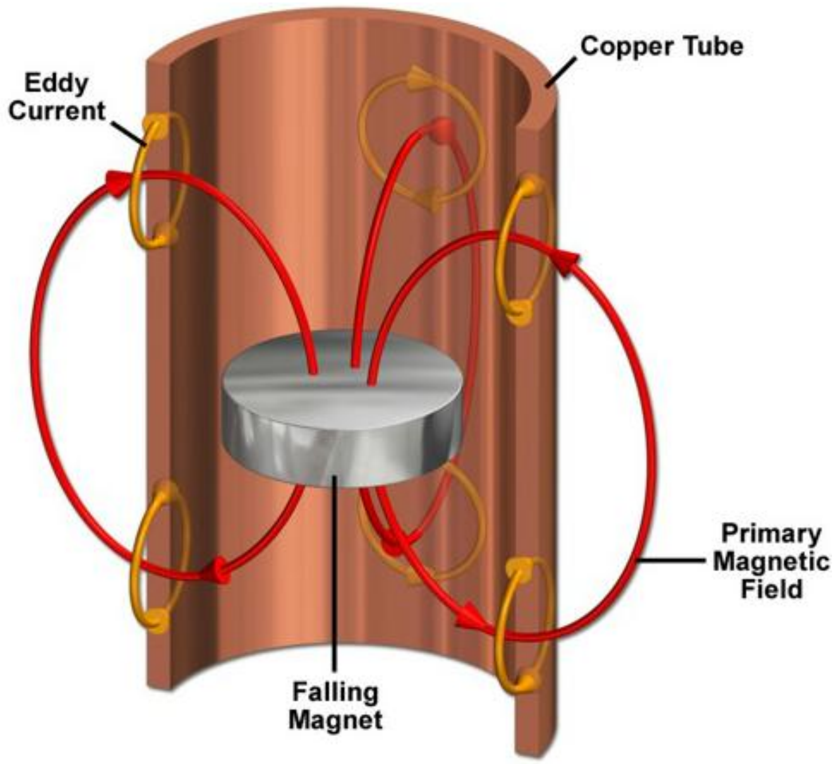

Figure 9. Eddy currents induced in copper pipe by falling magnet. [23]

So eddy current induced by a changing magnetic field in the conductor. The electrons in a copper pipe are moving. As they move these currents also create a magnetic field around them (Secondary Magnetic Filed, Fig. 10). Lenz's Law states that the magnetic field created will oppose the original magnetic field. These two field will oppose each other and that exerts a braking force on the falling magnet. It falls slower! Since PVC is a nonconducting material, the magnet accelerates to Earth as expected.

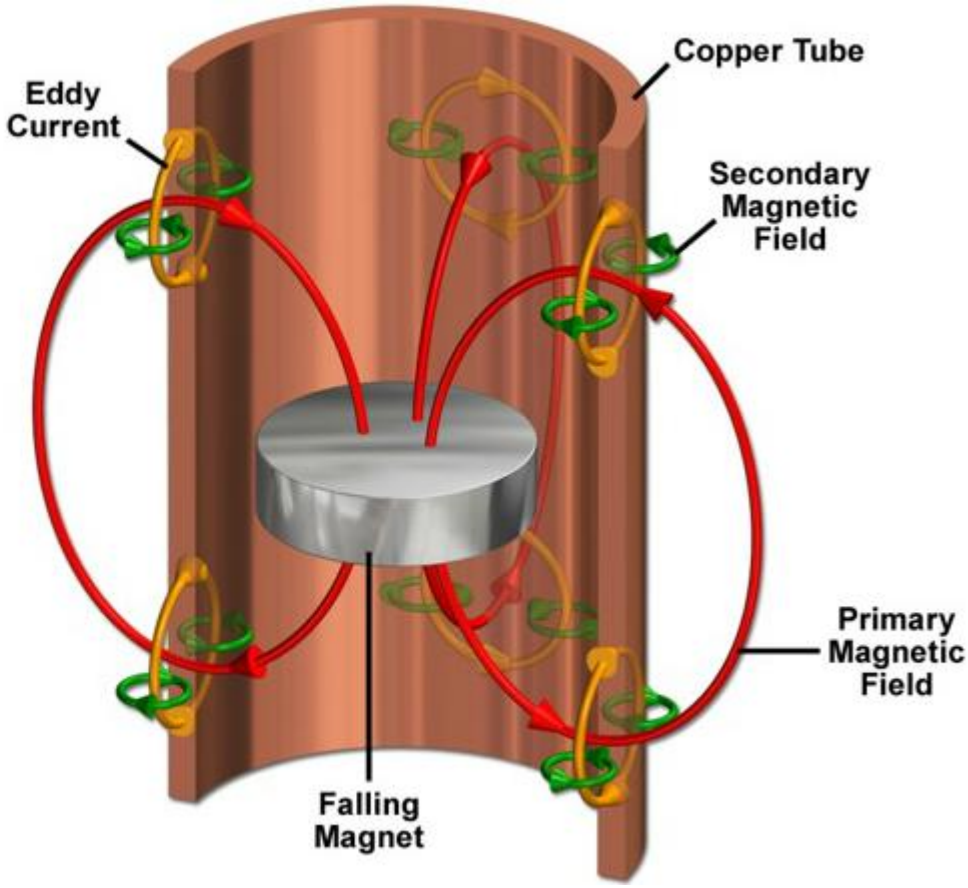

Figure 10. Secondary magnetic filed created as oppose to the orogonal magnetic filed. [23]

4.3 Eddy Current Separator Theory

As demonstrated in the previous section eddy currents slowed magnet's falling down in copper pipe. As soon as Lenz's Law states that secondary magnetic field opposed to original one it can be used to give a direction to material. There is equipment with called eddy current separator which uses this phenomenon for separate nonferrous conductors (color metals such as copper, aluminium) from dielectrics (such as plastic, wood, etc). As soon as we found that copper is a very good conductor and stainless steel has much worse conductivity it was concluded that this equipment could be used for our separation task and we can apply the method based on Lenz's Law. Detailed information about occurred experiments will be provided in Chapter 7 of this thesis. Now the theory of such eddy current separators will be considered. How it works? The main idea of this equipment is schematically represented on the Figure 11.

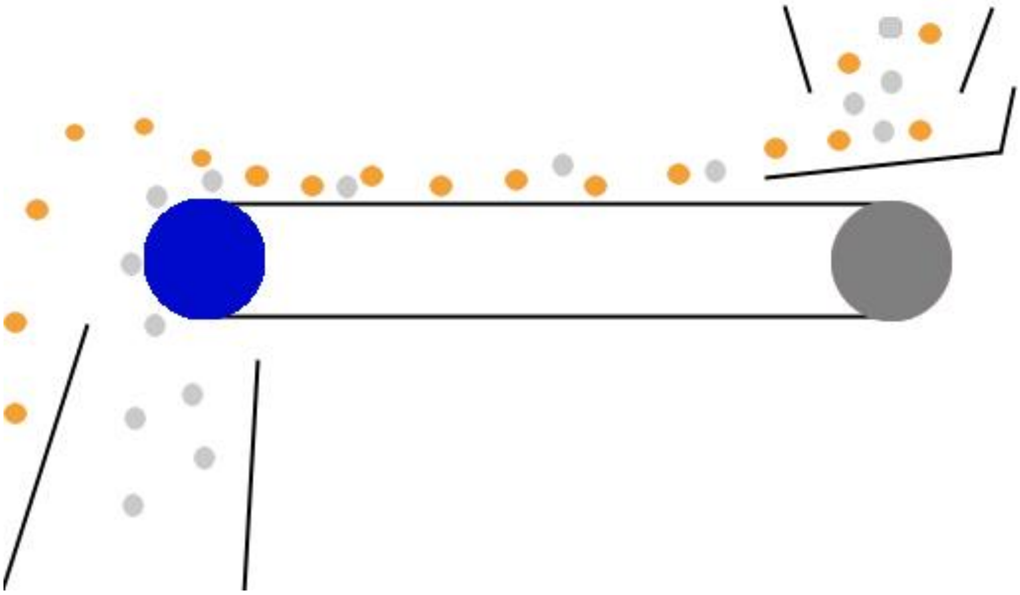

Figure 11. Eddy current separator.

The main work of the Eddy current separator is based on the different electrical conduction of metals and non-metals. The eddy current separator usually consists of a short conveyor driven from the feed end and a rapidly rotating system of magnets. It generates high-frequency changing magnetic fields. The conveyor makes the waste flow to rotating induction pulley which is incorporated in the head drum.

By changing the magnetic fields the flow of eddy current in the metals can be increased. This eddy current works in the opposite direction to the nearest pole of a magnet. When metals come near to the magnetic field, they get lifted and expulsed to one appropriate collecting canal.

The force depends on magnetic field frequency and conductivity of particles. In non-ferrous colours metals like aluminum, copper which has high electrical conductivity the eddy currents are big because of it and, therefore, objects are jumps at the long distance during separation process. In the ferrous black metals big eddy currents are also found, but due to magnetic field the attractive force to the surface of the drum dominates over the repulsive force. Materials with small conduction are almost not affected by the generated magnetic field and therefore drop straight down.

In practice an optimal removal can be achieved through adjustment of the separator. Eddy current separating systems of the modern generation are capable of separating even small 2 mm particles [24]

Initially, these separators are designed to separate non-magnetic metals (conductors such as aluminum, copper) from non-metals (dielectrics, such as plastic, wood). No example their use for the separation of metals could be found. But as in our case the electrical conductivity of steel is much less than copper, so it was concluded that such equipment can be used for separation. Some experiments have been made and results was presented in the Chapter 7.

4.4 Pulsed Electromagnetic Sensor

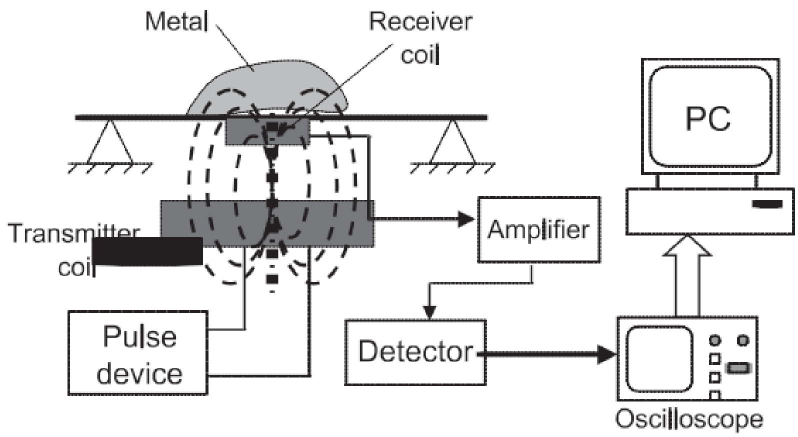

Figure 12. Experimental set-up of the PEMS. [25]

In a one research paper another method of separation based on the same laws mentioned above was presented. The authors developed a prototype of pulsed electromagnetic sensor (PEMS), which is utilising the difference in electrical and magnetic properties of metals for automatic sorting of scrap stainless steel. [25] The design of a prototype being developed at Delft University of Technology presented on the Figure 12.

The developed PEMS prototype consists of a pulse generator, a transmitter coil and an array of receiver coils. After amplification, the signal is analysed by an electronic unit that is able to detect stainless steel from other non-ferrous particles based on differences in electrical and magnetic properties.

After successful testing of PEMS they constructed some separator using this PEMS sensor (Fig. 13).

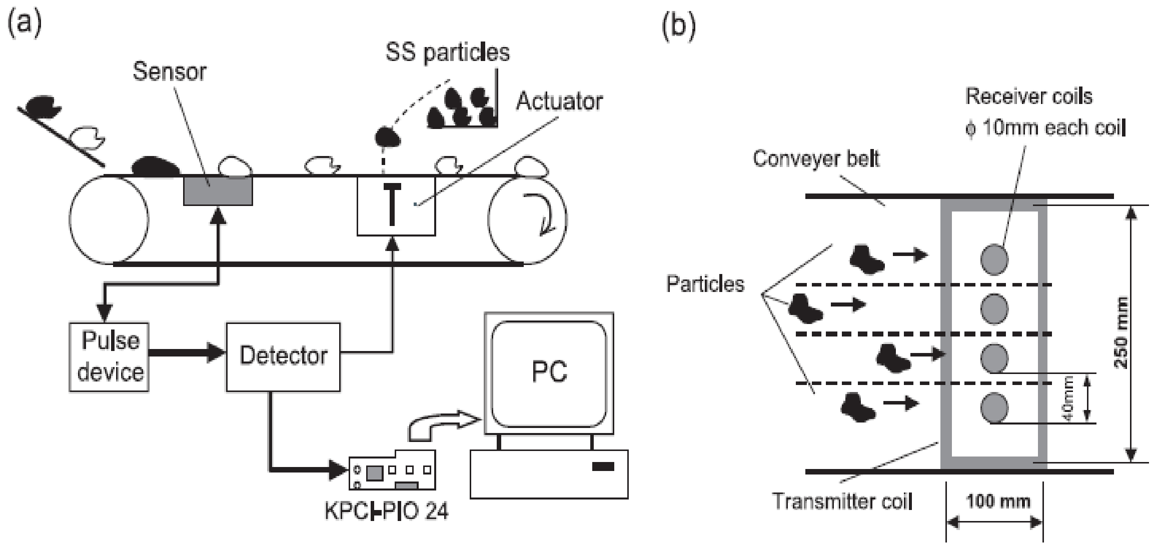

Figure 13. (a) Experimental set-up for SS separation using the PEMS; (b) sensor geometry. [25]

Only zone I is analysed by the system from the signal. Keithley KPCI-PIO24 data acquisition card was used to send the data to a computer. When a stainless still particle is detected the electronic unit evaluates the signal and transmit the signal to digisation unit. The particles that are detected by the PEMS are removed from the stream by an actuator, which is activated by the processing unit. This mechanism has pneumatic hammers installed under the conveyer belt. These are controlled by the PEMS system.

Researchers have achieved good results. The PEMS system automatically identifies and separates scrap stainless steel from other non-ferrous metals based on electrical and magnetic properties and the experimental results shown that 95% of the stainless steel can be recovered with a grade of almost 100%.

However, this method has a serious problem and cannot be used in our case. This system is designed for the separation of materials that move through the conveyer without overlapping. In our case, this is difficult to achieve.

5 SORTING BY COLOR

As mentioned earlier, the color is a clear difference between the two metals copper and stainless steel. In Finland under VTT Technical Research Centre of Finland it has benn cariied out an experiment how to sort scrap metal with colour vision and inductive sensor array. This experiment was carried out by Matti Kutila and Jouko Viitanen from VTT Technical Research Centre and Antero Vattulainen from Kuusakoski Oy and result of experiment was collected to research paper “Scrap Metal Sorting with Colour Vesion and Inductive Sensor Array”. [26]

Figure 14. The sorting machine Kombi with inductive and colour camera sensing systems. [26]

5.1 Colour Vision and Inductive Sensor Array

This experiment has been carried out on machine called Kombi (Fig. 14). The setup was based on the color difference in a CCTV signal. The differences were made using the red channel as the common component from which the green and blue were compared. Metals like copper and brass brings signals with a strong red component. The blue component is more significant for stainless steel and aluminum. The hardware of the system was based on Sony XC-003P CCD matrix camera with a sensor elements for the three colors. The camera separates adjustment of the gains of the color channels. The matrix camera was for Kombi. In order to get noise attenuation and less demand for computational power, neighboring pixel values were balanced. Color cameras were less sensitive than black-and-white one. That is why researchers used fluorescent bulbs with good efficiency. The inductive system had 52 sensors that calculated the electric properties of metals. The output of the inductive sensor depends both on the induced eddy currents and the magnetic properties of the metals. Actually, the sensors are used for on/off triggers to detect the approach.

Dirt was complicating the task. We knew that the result of sorting depends on used image pre-processing techniques. Researchers have described proper digital filtering which was an important thing there. In some cases, it was enough to use only the inductive sensor system or the machine vision system. But in some cases fusion of the decisions of the two setups was compulsory to get a better result.

At the primary level of the process the main thing was to remove the noise and irrelevant data from the image. Many metals could exist in a single image but researchers classified them separately. Dirty and bad pixels were separated from the image. The next filtering was done by averaging the measurement points. That process mainly removed all the dirt and disturbance.

In color space defined by the red, green and blue components, the differences related to the red channel were measured by us. The boundaries for the clusters which form the different classes were made for each metal in the two-dimensional space. All the points in the metal region were used by us for measuring the optical properties of the metal.

Researchers have used two machines for the separation conveyor. The one separated the stainless steel from the metal and another one recognized the reddish metals. In total 4646 kg of scrap metals were sorted. The results said that about 80% was separated correctly from the two machines. The main problem was made by aluminum which was known to all. The quality of the sorted metal was quite good. It was 80% pure which meets the first level of industrial requirements. The purity could be increased but this would take the expenditure in a higher level. In the laboratory the purity was got up to 90%. But researchers were able to take the purity to 80% which was enough. The stainless steel and colored metals were finely separated when the speed was below 1.5 m/s.

5.2 Market Research

There was found equipment on the European market which is able to separate metals by means of spectral analysis. The companies who are selling such equipment are, for example:

Steinert Elektromagnetbau GmbH
SPECTRO Analytical Instruments GmbH
TITECH GmbH
S+S Separation and Sorting Technology GmbH
Bakker Magnetics bv

Figure 15. Colour Sorting System FSS. [27]

There is example one of such equipment on the Figure 14. This is Colour Sorting System FSS from Steinert Elektromagnetbau GmbH. In the brochure says: "It separates products by surface colour, like copper from brass, cleans e-scrap from printed circuit boards; it sorts minerals and other bulk material. [...] The Colour Sorting System FSS detects the colour differences in bulk materials. Criteria for the system are colour, brightnes and particle size and shape. All this can be adjusted in the individual teach-in procedure, which is programmed at the very beginning. The Colour Sorting System is much more sensitive to colour and brightness differences than the human eye." [27]

How does the FSS work: The material which will be sorted is fed to a long conveyor where it is homogenized, distributed and stabilized in the correct position. Then it comes to the detecting unit in which it is lightened with modern LED's mounted camera system, giving it a homogeneous light source. The reflected light is recognised by a camera which a computer analyzes within seconds and the air jets get activated according to the plant. The discharge of the conveying system mounts these things.

The size and shape of the particle are directly related to the air jets and duration of the single blast. The colour and brightness features relevant for sorting are assigned to areas within the colour circle. It also carries an object recognation process. The engineers have designed the camera optics in a way that have included an automatic cleaning system. The optics are found in a place with an increased air pressure which, like a curtain, uses an airflow in order to stop dust or moisture.Water jets and horizontally arranged wipers clean the optics at the time of operation. A further point providing for easy maintenance to the hardware components. The throughput of the STEINERT Colour Sorting System FSS is able to rich 10 tonnes per meter and hour, depending on the materia. The size of grain are from 5 to 250 mm.

The disadvantage of this method lies in the fact that the material should not have dirt, otherwise spectral analysis did not yield positive results. But if apply it to Danfoss, their waste has no dirt. However, the main problem is the following. Use of such equipment requires, in our case, that the pieces of metal will be supplied to the analysis camera separated from each other (this is not about mechanical connection, but imposition is not permissible). To realize such in practice is very difficult and it has not been found solutions for that at least yet. So here we faced with the same problem as for the PEMS system mentioned in Chapter 4.4

6 MECHANICAL DISCONNECTION

As we have seen there are ways of separating these metals from each other. In the case of the color separation is necessary that each piece fell into the field of view separately from the other. It is almost impossible. At least the solution has not been found. In eddy current case there is no such requirement to provide separated pieces. However in both cases it is necessary that metals were separated from each other mechanically.

We remember that a mechanical connection is obtained by punching. The edges of the pieces are rounded and pieces are stick to each other. This issue will be considered in this chapter of the thesis.

6.1 Falling-blowing method

It was figured out the theoretical method of mechanical separation of the two metals from each other, which is shown schematically on Figure 16.

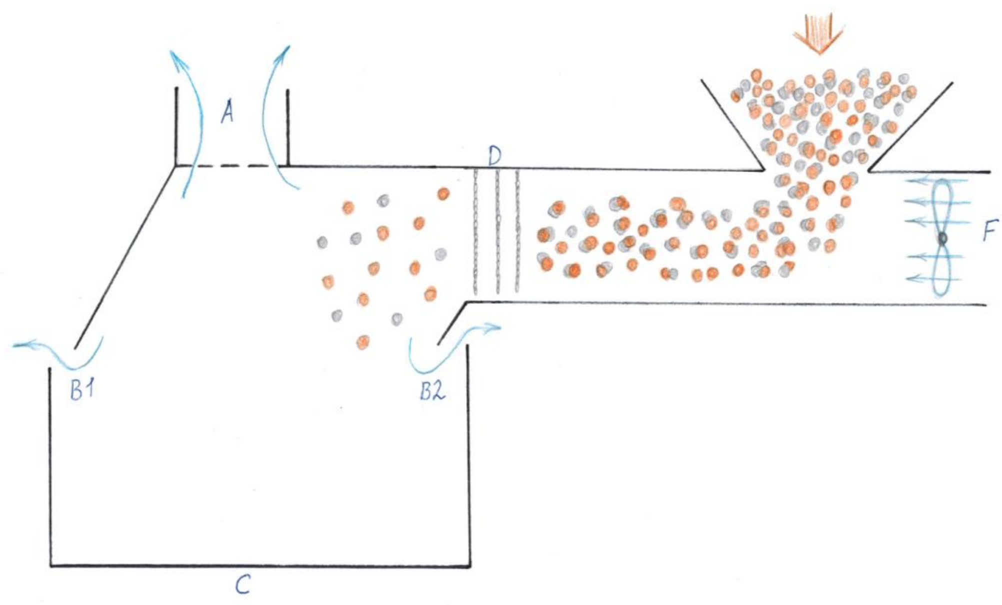

Figure 16. Schematic of falling-blowing method

In theory assumes the following diagram of the system. The metal is fed into the catcher in small portions and immediately blown away by a powerful stream of air from the fan side ("F" on Fig. 16) of the hanging chains. Striking of these chains ("D" on Fig.16) light mechanical connection breaks down and metals are separated from each other. Tubes "A" and "B" are designed to release air and equipped with protective netting. The product is collected at the bottom of the collector ("C" on Fig. 16). Practical research of this system not carried out for the reason that there was found another way of separation.

6.2 Mechanical vibration and shaking

Experiments were carried out on the separation of metals in the concrete mixer, but a negative result has been achieved. Metals have turned in a single whole that is proved to be even more connected with each other. However, another way deserves attention.

The first stage of separation is separation of metals from each other. After transporting the samples from the factory in a car in the usual plastic box it was not found pieces connected with each other.

After the transportation of waste it was found that there are no pieces joined together in the submitted samples. It has been suggested that normal vibration will be enough. There are special vibration tables on the market. When separating by vibration it is impossible to avoid overlapping of pieces due to the randomness of the process. Thus, this method does not help in the separation of metals by the color where the particles must fall within the field of view separately. However the experiments were conducted on the eddy current separator and the positive results were achieved. This is discussed in the next chapter.

7 SEPARATION BY DIFFERENCE IN ELECTRICAL CONDUCTIVITY

As mentioned earlier it was decided to try eddy current separator which is initially designed to separate non-magnetic metals (conductors such as aluminum, copper) from non-metals (dielectrics, such as plastic, wood). No example its use for the separation of metals was found. But since electrical conductivity of steel is much less than copper, so it was concluded that such equipment can be used for separation. Some experiments have been made in the research laboratory NPO "Erga" on colours-metals separator CMBT (Fig. 17).

Figure17. Colours-Metals Separator CMBT- ВП 1000. [28]

7.1 Separation on Colours-Metals Separator CMBT

About 10 kilo of metal scrap was delivered to laboratory NPO "Erga" and company's engineers have carried out experiments. They processed those samples on Colours-Metals Separator CMBT and it was empirically concluded that separation of stainless steel and copper, by eddy currents separator series of CMBT is possible, but with one note.

Figure 18. Round shape pieces that should be excluded from separation zone.

It was found that round shape pieces of scrap (Fig. 18) won't be separated correctly and should be excluded from the separation zone. However, one solution was offered. [29] It is known knife cuts all shapes in the source material when punching radiators. It was suggested to make modernization of cutting knife to exclude round pieces (Fig. 19). It was tested. Half-curred samples are separating correctly.

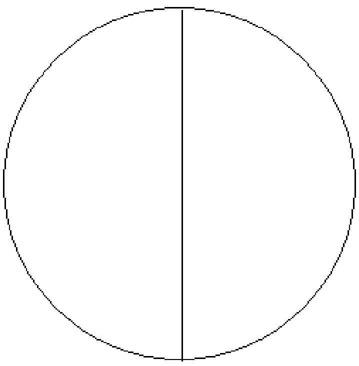

Figure 19. Cutting knife modernization

As for the first stage of separation - disconnection of metals from each other – it was noticed the following. After transporting the samples from the factory in a car in the usual plastic box it was not found pieces connected with each other. Also, when NPO "Erga" got it, there was not found such pieces. It was concluded that the normal vibration can separate pieces from each other. For this purpose at the beginning of the separator it must be installed a vibration table. This was also represented by NPO "Erga".

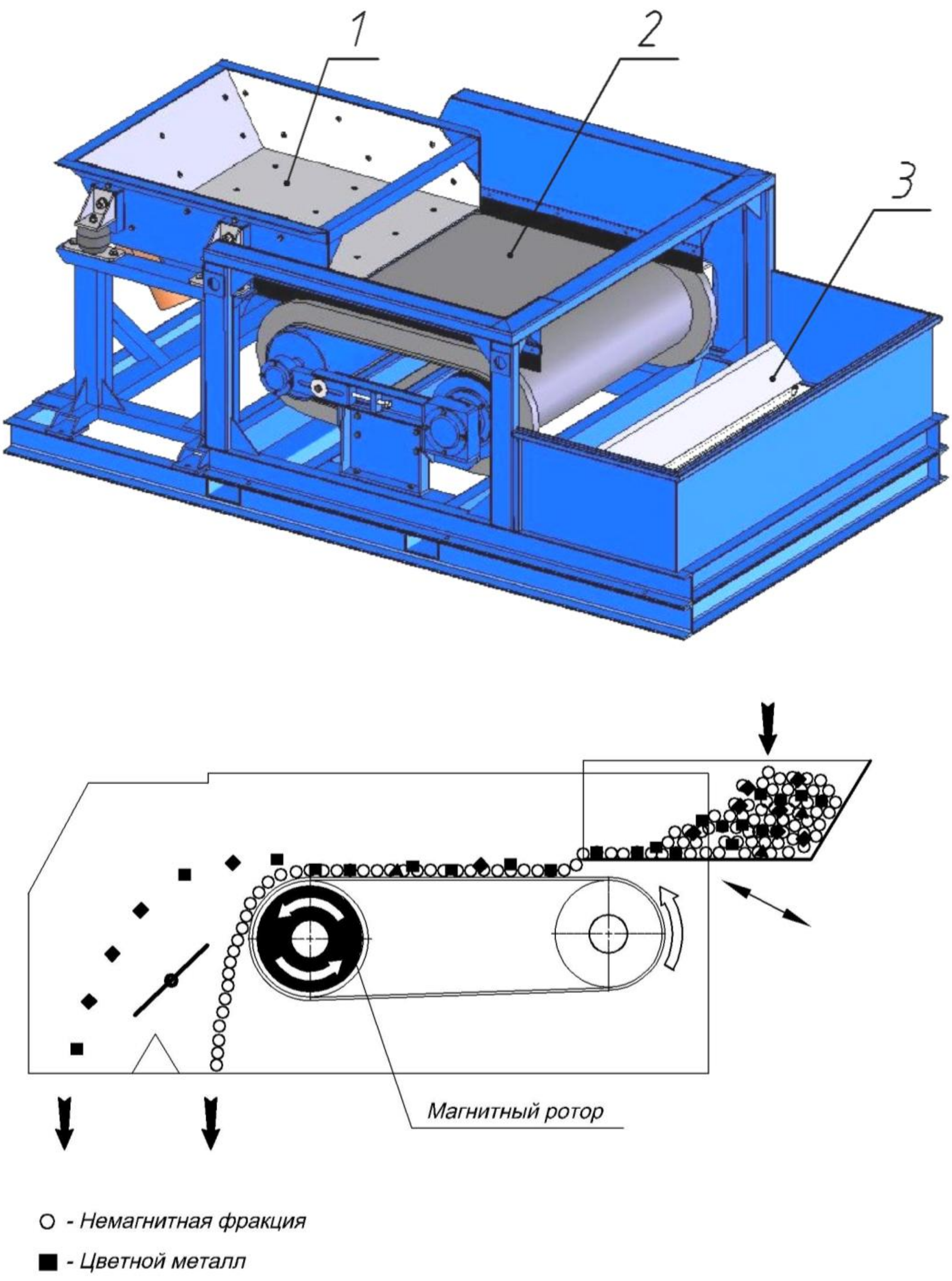

Figure 20. Scheme of a magnetic separator series CMBT. [30]

So the final solution would be the following (Fig. 20). Scrap is supplying to vibro-table (1) for better distribution on conveyor (2) and to disconnect materials from each other. Then onthe area of rotor we do separation. The behavior of copper (black square on the Fig. 20) similar as for non-ferrous metal - a good conductor, so the copper "fly" into the remote tray. Stainless steel (transparent circles on the Fig. 20) behaves as an dielectrics and falls down from conveyer to another tray.

It is not possible to be 100% sure that this vibration would be enough, since there was not presented a sufficient number of samples, rigidly connected with each other, but the separation of provided samples occurred successfully.

7.2 Separation on Eddy Current Separator LESV-65

Another experiment was carried out in China on the Longi Magnet Co.,Ltd factory on the Eddy Current Separator LESV-65 with Vibratory Feeder (Fig. 21). They also was provided by 10 kilo of scrap for natural experiments.

Figure 21. Eddy Current Separator LESV-65 with Vibratory Feeder. [31]

However the separation rate for one period had been around 90% only (Fig. 22). The following steps was suggested for better perfomance. It was said the following: " The problem is that small size of copper cannot jump that far to be discharged, and when we raise up the magnetic intensity to make copper jump farther, the weak magnetic stainless steel starts jumping, so small size of copper and stainless steel will mix up". [32] So was suggest to remove small size of copper out and separate it in the other time. However this is quite complicated task, because all scrap is mixed.

Figure 22. Separation results for Eddy Current Separator LESV-65. [31]

CONCLUSION

As a result of this research it becomes clear that the most suitable method of separation copper from stainless steel is based on the induction and eddy currents with pre-vibration on the vibrating table. In other words for the solution of the problem most correctly to apply the method separation based on differences in electrical conductivity of materials, so to use the eddy current separator.

The principles of operation of all devices are identical, but each has a specific. For every new factory it should be taking into account the specifics of its factory and manufacturing process. It may need to modify something, configure or upgrade. To automate the entire process may need to install the conveyor for feeding raw materials into a zone of separation if the manual loading is not applicable. But in general, it is clear that the separation of these two materials from each other is possible with almost 100% result. In the case of the NPO Erga it was needed just to modify the knife.

To search for a perfect solution it may need to conduct a deeper analysis of the behavior of these two metals depending on their shape, thickness, dimensions and it can be basis for some other new thesis. In this thesis it was not carried out the reasons for which the round pieces of steel did not want to be sorted. Perhaps it is bacause of influence of some other forces such as gravity.

Experiments have shown that the results may be very different. For example, the Russian company Ergo was reached 100% separation if exclude round components from separation. On the Chinese laboratory the result of only 80% has been reached. If a plant requires high quality solution then as we can see it is necessary to provide samples to various manufacturers of such equipment and conduct experiments. The same Was done during this research work.

The use of information from this thesis can help even more companies in Finland to find effective solutions for the separation of metal waste which has a positive impact on their financial situation and will also preserve the environment.

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