BAMB
BUILDINGS AS MATERIAL BANKS

METALS VALUE CHAIN REPORT

28-02-2019

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Co-funded by the Horizon 2020 Framework Programme of the European Union

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642384.

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INTRODUCTION

A huge industry is involved in mining the raw material, smelting it into billets or bars and processing it to create a finished product ready for use. We're talking of course, about metal products. Next to "virgin" metal (metal from primary resources, e.g. iron ore), recycled or 'scrap' metal is used to create products. Whilst the use of recycled metals saves a lot of energy and processes compared to virgin metals production, the use of virgin metal is still a necessity. This is due to the demand of metal products exceeding the supply of scrap, and because desired composition of metal products is achieved by diluting recycled metal with virgin material. Moving toward using 100% recycled, healthy metals for products will require a more symbiotic and collaborative approach from all players within the field.

In this report, the challenges of the metals recycling industry moving towards a circular economy are detailed. Both mechanical and health related issues must be dealt with, if the industry is to move to 100% recyclable and/or more recycled products and materials.

METAL USE IN THE BUILT ENVIRONMENT

Applications

Metals are used profusely throughout the building industry. Infrastructure, offices, industry, housing; Many rely on structural beams made of a metal alloy, mostly steel. Next to this application metals are also used for cladding (aluminium or copper sheets), drainage (rain pipes), wiring, window and door systems, ventilation, reinforcements (i.e. in concrete) et cetera.

Examples of steel, copper and aluminium in the built environment.

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Depending on the purpose of the product, different metals and especially alloys are selected. Alloys are combinations of different metallic chemical elements which are melted together into one product. Bronze is an example of an alloy consisting of 88% copper and 12% tin. Copper is traditionally used in wiring in pure form for its high conductivity, steel is used for structural beams and wiring in reinforced concrete for its strength and relatively low cost. Aluminium is used extensively because of its strength, lightness and easy formability.

Prominent metals in the built environment

Buildings contain many metal elements, for instance facades, heating, wiring, windows, structural elements etc. Frequently used metals are amongst others iron (often as part of a steel alloy), aluminium, copper and zinc. Out of these, iron and steel are ferrous, the others are non-ferrous. This report will focus on aluminium, copper and steel to visualise the challenges and opportunities in metal recycling, since these metals have a well-developed recycling infrastructure and are already being recycled in large quantities.

Ferrous

Ferrous alloys contain iron (latin name ferrum) as an alloying element. Major ferrous alloys are steel, cast-iron and wrought iron. The most prominent of which is steel, with approximately 1630 million tonnes produced in 2016. (World steel recycling in figures 2012-2016, 2017)

Crude or raw steel (steel in the first solid state after melting) is produced out of pig iron, which is created from iron ore using a Blast Furnace (BF). Creating a ton of pig iron requires approximately 13.5 gigajoules (GJ) or 3750 kWh of energy, which is more than the yearly electrical energy consumption of two average European citizens in 2016. (Eurostat, 2018) The next step in the process is a Basic Oxygen Furnace (BOF) which reduces the amount of carbon in the iron. This step requires 11 GJ per ton. Alternatively, an Electric Arc Furnace (EAF) requires 2.25 GJ per ton of steel. (Fruehan, 2000) An EAF cannot use iron ore as an input and is solely used to melt scrap steel.

Comparing these processes, the production of virgin steel requires up to 5 or even 6 times more energy than the production of recycled steel. On top of that, both the BF and the BOF use fossil fuels in the form of coal as the primary energy source. The EAF on the other hand uses electricity, which can be sourced from renewable as well as non-renewable sources.

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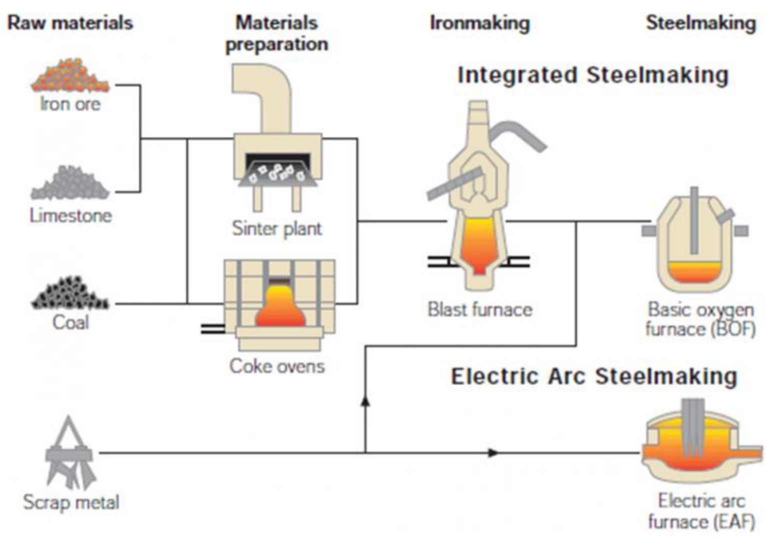

The process of steelmaking with BF, BOF and EAF. (steelconstruction.info, n.d.)

During the BF, BOF and EAF processes, slag is produced as a byproduct. Slag is a 'mixed waste' product containing amongst others iron-, calcium- and aluminium-oxides. It also contains heavy metals like lead, chromium, zinc and vanadium. Slag is used in some processes involved in metal production but is mostly used for road base and cement incorporation. (Gomes, 2006)

The production processes of other ferrous metals resemble that of steel for the most part. The difference between the alloys derives from the addition or exclusion of elements that give the alloy certain properties. For instance; the inclusion of a small amount of carbon will greatly increase the tensile strength of the metal compared to a pure iron composition. In the case of stainless steel, chromium is added to reduce the oxidization of the finished product.

Non-ferrous

Non-ferrous alloys do not contain the element iron. Prominent non-ferrous metals in the building industry are aluminium, copper and titanium.

Aluminium and its alloys have become increasingly important in the building industry because of several interesting properties. Next to being very light due to low density, it is very strong and relatively corrosion-resistant. Corrosion resistance stems from the outer layer of the aluminium, which after oxidation insulates the rest of the material in a process called passivation.

Aluminium is won mostly from bauxite ore, a sedimentary rock rich in aluminium. Australia is the largest delver of bauxite, producing 83,000,000 tonnes in 2017, with China being second at 68,000,000 tonnes. (Ober, 2018)

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The production of virgin aluminium is highly energy-consuming. It requires two steps, the Bayer and Hall-Héroult (electrolytic reduction) process, which generate aluminium oxide also known as alumina from the bauxite and pure aluminium from the oxide respectively. This pure aluminium goes to the casthouse where it is remelted to remove the excess iron, silicon, copper and other elements, and cast into moulds to solidify. (aluminium leader, n.d.)

The large smelting facilities are situated at locations where electricity is abundantly available and cheap. During the electrolytic Hall-Héroult process, large amounts of carbon are used as cathode. This carbon is turned into CO2, which is released into the atmosphere. Aluminium fluoride is added to reduce the melting point creating fluoride gasses. In modern facilities, some of these gasses are collected and recycled through absorption by alumina, to be reused in the production process (Green, 2007)

2 kilograms of bauxite yield approximately 0,5 kg of aluminium but require on average 15 kWh/kg (54 GJ/ton) of energy. By far the largest producer of aluminium is China. Out of the 64,338,000 tonnes produced worldwide in 2018, China produces 36,485,000 tonnes, or 57%. (World Aluminium, 2018) Second on the list is Russia with a production of 3,600,000 tonnes in 2017. (Kay, 2018)

As in steel production, aluminium production creates byproducts like slags. They are formed because of the use of salts to cover the molten aluminium during production to prevent oxidation. (Overduin, 2010)

Copper is mostly won from sulphide-ores. These ores are crushed, and copper concentrations are increased by froth floatation or bioleaching. Next the material is heated with silica in a flash furnace removing iron. The resulting matte is roasted and the cuprous oxide that forms is heated to create blister copper. A final refinement step takes place in the anode furnace creating fine-refined copper. (Alliance, 2018)

RECYCLING METHODS

Metal products are being recycled on a global scale throughout all industries. With every industry tailoring their own recycling pathway to fit the corresponding products. In general, all recycling in the metals industry follows some iteration of the following steps:

- Collection/Recovery
- Sorting
- Processing
- Shredding
- Melting
- Purification
- Moulding

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Collection/Recovery

The way that metals are collected or recovered depends on many features of the final product. Size, structural context, chemical properties, etc. Lead used in batteries for example is recycled with a high degree of well supervised recycling services due mainly to the toxicity of the metal. Copper is a very popular non-ferrous metal with e.g. copper thieves who often risk their lives stealing it from train tracks just to sell it at high rates for recycling. Though not all metals are recycled to the same degree, almost all are considered too valuable to waste.

Companies understand the value of metal products very well and some have specialised in their recovery. In the building industry, contractors specialised in deconstruction/demolition, collect metals and sell them to scrap collectors who sort and process them.

Sorting

Whether the used/scrap metal comes from industrial waste, building deconstruction or domestic recycling, all metal needs to be sorted. To properly recycle all the metals we use, they need to be separated before they are melted down to create new products. Sorting the products is a first step in this process. Most sorting still takes place by way of visual identification. Workers determine what kind of product is in the scrap and sort them accordingly. Ferrous metals contain iron, which has magnetic properties and thus can be separated from non-ferrous metals using magnets.

Multicomponent products however, which consist of several materials, aren't easily disassembled and separated. A TV is such an example. The different materials attached to the metal products are removed and may have their own separate recycling pathway.

Processing

Once the products have been separated largely based on their core components, they are processed. This usually means they are compacted to save space. Cars, window frames, lamp posts; all are compressed to the minimal volume to reduce transport costs.

For some metals, processing may involve cleaning (removing oil, grease and other contaminants) and decoating/delacquering. For most steel products, the decoating process takes place automatically when the scrap is heated for melting, essentially burning the top layer from the metal underneath. This process requires large amounts of energy and generates

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the decoated metal and the surface treatment in a gaseous state. Steel surface treatments are usually burned off in the EAF, leaving behind approximately 15-20 kg of dust per ton steel. This dust can contain among other things zinc (Zn), lead (Pb) and cadmium (Cd). The metals in this dust can be recycled, but only 45-50% actually is. The rest is landfilled, potentially leaching toxic metals. (Antrekowitsch, 2015)

For Aluminium a similar process can be used. (Schlesinger, 2014) But in advanced facilities such as the ones used by Hydro, pyrolysis is used to remove surface treatments, residual polymers and other contaminants. (Jaroni, 2011) This process is performed without oxygen in a sealed environment.

Not all recycling facilities have the proper equipment to deal with the emissions that occur from this decoating through heating process. Which is why a lot of scrap material is still exported to facilities that do, or to countries where emission standards are less stringent than for instance the Netherlands. (Overduin, 2010)

Shredding

The compacted products are shredded into smaller fractions to facilitate processing. Sometimes it takes multiple steps to shred the material to the proper size for further processing. Another function of shredding is to create more surface area and reduce the amount of energy needed to melt the material down.

For many years this phase was the last phase before melting down the metal. Further purification to guarantee the quality of the recycled metal took place only after melting. Modern techniques have created additional sorting steps. Machines now use X-Ray Fluorescence to determine the composition of the individual pieces of scrap on a conveyor belt. These fractions are then separated by air jet propulsion. This not only distinguishes between metals and non-metals but can also separate different metals. For some machines this precision is even used to distinguish between different alloys. (Weiss, 2015)

With this new technique it has become possible to select metal fragments regardless of their surface treatment. Nickel coated brass for instance will still be recognized as brass by the machine. This technology offers near perfect pre-melting separation. Unfortunately, this type of high-tech solution is not available everywhere and therefore used on only a very small portion of the available scrap.

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Melting

During the next step, scrap metal is melted down in a furnace. Each metal has specific properties. The furnaces use these properties such as density and melting point and are specifically designed for a single metal type. Melting metal requires a large amount of energy, but the pure nature of the scrap metal allows for fewer steps than the production of virgin material. This makes the production of metal from scrap far less energy consuming. For aluminium for instance, scrap is melted down, purified and mixed to create the desired alloy, thus not requiring the energy intensive Bayer and Hall-Héroult processes.

Purification

The melted metal still contains impurities which can be removed through electrolysis. This process uses electricity to transport ions from an impure composition to a pure composition.

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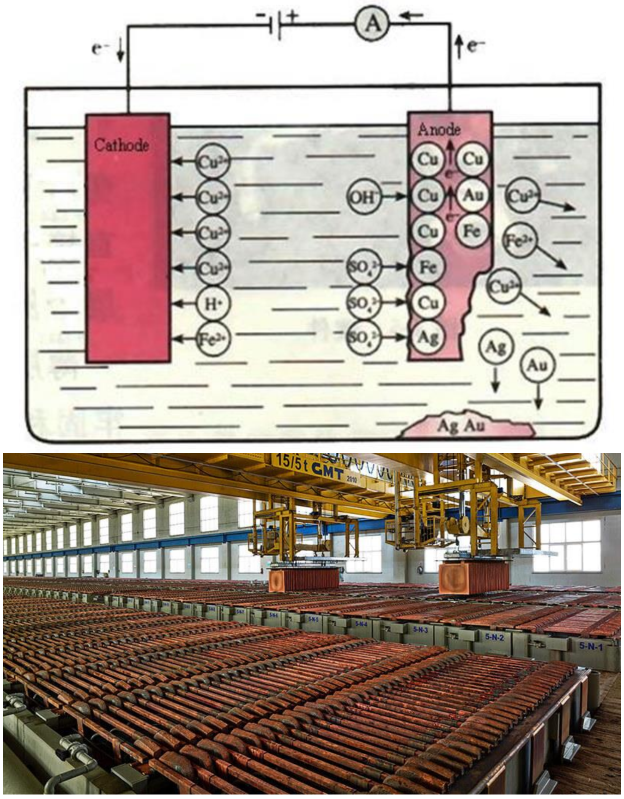

Top: schematic drawing of copper refinement (source: Selection of Stainless Steel for Cathode Plate in Hydrometallurgical Process by Chi Zang). Bottom: A copper electrolytic plant. (Copper-recycle.com, n.d.)

Another possibility is to use the different melting temperatures of metals to create pure crystals, which can be removed. The resulting solid purified metals are now ready to be molded.

Purification is not always possible because of technical reasons, or because it is not economically viable. However, in most cases the step is not applied at all. In practice, when a producer applies scrap metal and desires a certain composition, virgin material is added until the desired composition is achieved. This way large volumes of metal can be made with recycled scrap without going through a costly purification step. (Bjorkman, 2014)

Molding

The metal is once again melted and molded into ingots or billets. The dimensions can vary drastically depending on the production requirements for the new metal products. This is the

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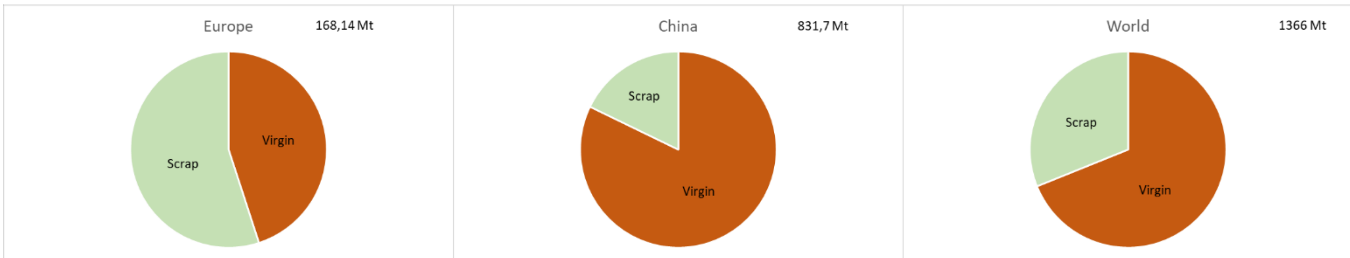
last step in the process before the metal is transported to a facility where it will be applied in a new product.

RECYCLING VOLUMES

Steel

For the metals mentioned so far, extensive recycling methods are already being applied. In 2017, 425 million tonnes of scrap were produced. In that same year 1366 million tonnes of crude steel products were made. Scrap usage is depicted in the diagram below.



For Europe, 55,5% of its 168,14 million tonnes (Mt) of crude steel came from scrap. Leading steel producer China produced only 17,8% out of 831,7 Mt from scrap. For the world this was 31,1% out of 1366 Mt. (Recycling, 2018)

Worldwide the recycling rate of available scrap steel was estimated at 86% in 2014 according to the Steel Recycling Institute. (Steel Recycling Institute, n.d.) This makes it the most recycled material across all industries.

A worrying trend in metals recycling is the amount of scrap that is exported. 82% of all steel scrap from the Netherlands is not processed within its borders, with more than half going to countries like China, Turkey, the United States and Bangladesh. (Recycling, 2018) Collectors of scrap in the Netherlands have stated at the December 12th Circular Economy Lab in 2018 by the Utrecht Sustainability Institute, that it is cheaper to send scrap to Shanghai in empty containers leaving the port of Rotterdam, than it is to transport it to a Dutch city 200 kilometers away.

Tata Steel Europe used approximately 1,8 Mt of steel scrap in 2017. Because the demand for steel still exceeds the amount of scrap available, virgin material is still needed. Tata has been piloting a new technique in the HIsarna process to be able to use greater quantities of scrap. (Bonnema, 2019)

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Aluminium

In 2015, 5 million tonnes of aluminium scrap were processed in the United States. In 2006 the total amount of recycled aluminium scrap was 7,8 million tonnes. 24,4 million tonnes were added to the total aluminium in use. Unfortunately, 3,5 million tonnes were not recycled. (Menzie, 2010)

Recycling rates vary greatly between sectors. According to the International Aluminium Institute, recycling rates of aluminium in the transport and building sectors are around 90% and 85% respectively. In the packaging industry recycling rates may vary from country to country between 30% and close to 100%, with a global average of close to 70%.

One study by the Technical University of Delft (The Netherlands) found that collection rates for aluminium in European Buildings was exceptionally high. Even though only 1% of the total mass of these buildings was aluminium, between 92 and 98% of the aluminium was collected. (European Aluminium Association, 2004) This shows that the value of the metal is well understood.

However, as with the steel scrap, low-quality aluminium scrap is exported to countries with lax legislation on emissions. (Overduin, 2010) In an interview conducted as part of this report, Wijnand Loven , Environmental Manager at Hunter Douglas confirmed that the scrap accepted for recycling has to comply to strict requirements. These pertain to the composition of the scrap. The aluminium can for instance not have any polymers, oils or coatings. (Loven, 2019)

Copper

According to the International Copper Association, 35% of all copper currently in use stems from recycled sources. Between 2006 and 2015, approximately 102,5 million tonnes of copper were part of post-consumer scrap. 51,3 million tonnes of this made it back into circulation as recycled products. For one of the most valuable metals in the recycling industry, a recycling score of 50% is rather low. 28,2 million tonnes of copper scrap were estimated to be lost due to the post-consumer scrap not being collected for recycling. 22,5 million tonnes were lost during separation.

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Challenges with Conventional Metal Recycling

Metal recycling has become a very profitable business with a worldwide estimated value of approximately 446,472 million dollars during 2016-2022. (Takur, 2016) Vast amounts of material are being processed daily. Even in countries where recycling is implemented in everyday life, different products can have very distinct recycling pathways. Aluminium cans used for food and drinks are usually very well separated from other waste streams, but other metal products may not be given the same treatment.

Value

The driving force behind the recycling of metal is the value that the metal still has. The price of scrap steel is currently around €135 per net tonne for structural steel. (Leblanc, 2018) The value of scrap metal has increased with the technological progress in the recycling industry. This both drives and limits the amount of recycling that takes place. Highly abundant and extractable metals from secondary sources will be recycled at higher rates than metals in lower abundance and more challenging products.

The economic factor drives the recycling infrastructure. Without it, companies and consumers wouldn't be able to recycle even if they wanted to. Differences in recycling rates of materials can be traced back to an economic incentive to recycle and the quality of the existing recycling infrastructure.

Additionally, there is a discrepancy between the price of virgin and scrap material. In some cases, it is still cheaper to buy virgin steel than it is to buy recycled steel as was mentioned at a conference in Utrecht by Hans Hage, Principal Researcher at Tata Steel. (Utrecht Sustainability Institute, 2018) This removes the incentive for the producers to buy recycled steel, which removes the incentive to produce recycled steel.

Longevity

Many metal products used in construction have a long first-use period. It may be decades before the steel, aluminium and copper from a building become available for recycling. Products like cars usually have a shorter defined use period and packaging products such as aluminium cans become available for recycling even more rapidly.

Recycling rates in the building industry for certain metals have been shown to be high. (European Aluminium Association, 2004) But due to the turnover rate being low, this stockpile of valuable metals is not enough to support the demand.

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Product design

To recycle valuable metals at the highest rate possible, product design needs to account for end of use (EoU) scenarios. If products are only designed for one use phase, recycling can become more difficult. Many recycling facilities cannot process products in which metal is irreversibly attached to other materials, which was confirmed in an interview with the Environmental Manager of Hunter Douglas in the Netherlands. (Loven, 2019) (Overduin, 2010) An example is the aluminium used for sealing food containers, which is bonded to a polymer (often PVC). Reversible design of buildings is an example of growing awareness of the value of materials in EoU scenarios. Products and buildings need to be designed for disassembly for the individual components to be recyclable. The identification of materials and the availability of details about their compositions and potential next uses support high-level recycling.

Impurities

An important challenge in recycling metals at high levels of quality are the formation of impurities in the recycled metal. Impurities stem from unwanted, or 'tramp' elements making their way into the alloys. For the properties of the alloy to suit the purpose of the product, the chemical composition is of high importance. Even a very small amount of tramp element contamination can cause problems. For instance, 0,3% tramp copper is no problem for stainless steel alloy 304, but higher amounts may make the material more brittle. (Stachowiak, n.d.) To ensure the quality, the molten recycled metal is analyzed using spectroscopy to determine the composition.

Some impurities can be removed through electrolysis, or through separation during the melting process. The latter is possible because due to different properties, a separate solid mass or liquid layer is formed during melting. Both processes require a lot of energy and time. They also create a new stream of waste, which can sometimes be used, but not always. However, the commonly practiced solution for reducing the concentration of tramp elements and creating the desired composition is mixing in virgin material, a process known as dilution. (Bjorkman, 2014) This makes it impossible to create metal products from 100% recycled material, unless dedicated takeback in combination with information about the source and composition of material are available. Materials Passports have been developed as a part of the Buildings as Materials Banks (BAMB) project to ensure the availability of this information. (Materials Passports, n.d.)

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Causes of impurities

The most prominent causes of impurities are:

- Contamination during sorting and separation
- Contamination because of bad product design (without incorporating EoU scenarios)
- Unforeseen peak contamination

During sorting and separation, errors can result in scrap steel finding its way into an aluminium alloy, or lead becoming part of a steel alloy.

Another source of impurities is product design. A sheet of pure aluminium is easy to recycle. The aluminium from a computer requires a lot more effort to extract. The extraction becomes even more difficult when the metals are attached to other materials using adhesives. Many products that enter the consumer market today have been designed solely to perform their function during the first use phase. Without looking at the EoU scenario, products can become too complex to recycle. (Reuter, 2013)

The contaminations mentioned above cover most problematic trace elements in metal recycling. However, unforeseen contaminations can take place by accident. A case of radioactive pellets being recycled with normal steel in Mexico in 1984 illustrates this. By accident, an electrician accidentally sold what he thought was just a tungsten (wolfram) wheel to a junkyard. The wheel contained pellets of radioactive cobalt, which were used in cancer treatment. The pellets were picked up by a sorting magnet and found their way into a recycling stream for steel. 300 curies ($1{,}11*10^{13}$ Bq) of radioactive cobalt were processed and turned into table legs for restaurant tables, and steel rods for reinforced concrete. (Blakeslee, 1984)

This mistake was only discovered when a delivery truck took a wrong turn and tripped a radiation alarm. The source was traced to the junkyard, and the table legs and steel rods were tracked down. A potential disaster was therefore quickly prevented, but only by accident and because radioactivity can easily be measured. If a contamination like this happens with other harmful metals that are not so easy to detect, the effects on health and safety can be far reaching.

The metals industry is a perfect example for the value of recycling, and it lays bare the challenges that must be faced. For most metals, a 100% recycling rate is theoretically possible. Also, for most of these metals, value in proper recycling is high, since extracting the elements out of the earth and processing them into the final product takes much more energy and time compared to recycling the metals that are already in use.

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SURFACE TREATMENTS

Surface treatments are used to give metal products important aesthetic and functional characteristics. They influence health- as well as environmental aspects related to steel products ánd they influence the recycling quality of steel products.

Surface treatments give metals important characteristics that can range in function from aesthetics to anti-bacterial functions to anti-corrosion functions and many others. Traditionally, surface treatments were applied mostly to protect steel products from wear and tear. In more recent years, surface treatments that perform additional functions such as conductivity, heat distribution, anti-bacterial functions and air cleaning functions have entered the market. This chapter navigates how surface treatments influence materials health as well as the recycling process of steel products.

Steel

For steel products, the most prominent surface treatments in use today are zinc phosphate priming, chemical/powder coating, hot dip galvanisation and zinc spray metallizing. Galvanisation is often followed up by passivation, which may include the addition of the carcinogenic hexavalent chromium or chrome VI. (Holmes, 2008)

Zinc phosphate priming is used to paint steel surfaces to improve corrosion resistance and increase the aesthetics of the surface. It is used in construction, ship building and the automotive industry. The primer can be applied by brushing, rolling or spraying, after which it forms a protective film.

Chemical or powder coatings consist of polymers and additives, but importantly do not need a solvent. The particles are positively charged before being sprayed onto a grounded metal surface. After the spraying, the surface is heated to melt the coating, let it flow out and set in a crosslinked network. Common types of polymers used for this type of coating are polyester, polyurethane, polyester-epoxy, straight epoxy and acrylics.

Hot dip galvanisation is a process in which steel is coated with zinc at 449°C. The zinc reacts with oxygen, and the resulting zinc oxide reacts with carbon dioxide to form an oxidized outer layer that protects the steel underneath. It is used in products that are exposed to the outside environment. In this process the zinc alloys with the steel surface, giving a longer lasting protection against weather conditions.

Hot zinc spray is used as an alternative to hot dip galvanisation. In this technique the liquid zinc is sprayed on, creating a film of droplets on the steel surface. Zinc spraying is cheaper

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and can be used to create thicker coatings than hot dip galvanisation. Since there is no heat distortion as compared to the hot dip galvanisation process, zinc spray is often used for more delicate designs. The main preference for the hot dip process stems from the longevity of the corrosion resistant layer, which is much higher than for the zinc spray.

Aluminium

Aluminium surface treatments can be categorized in three groups. Electrochemical treatment, chemical treatment and coatings.

Electrochemical treatments make use of the electrical properties of the aluminium. The most commonly used method is anodizing. In this process, the metal is turned into an anode and submerged in an acid electrolyte bath. The aluminium reacts with the acid in the bath, oxidizing the outer layer of the material. This creates a corrosion resistant layer, which can be given different colours and appearances depending on the type of anodization that is applied. Varying methods can have varying impacts on the material.

Though the anodization process can itself already change the colour of the surface, dyes are often added to create a desired colour. For most colours, an organic molecule with or without added metal is used. Many of these organic molecules contain aromatic rings in their structure.

The chemical treatment of aluminium is used mainly to alter the structure of the outside layer. This is done to brighten the surface, or polish it, or to remove or roughen parts of the outer layer. It can also be used to remove organic compounds like oil or grease.

The coating of aluminium can be done in various ways, just as with steel. From lacquering, to chemical conversion coating, to priming with zinc and powder coating.

Use phase

Mainly the surface treatments of metals are used to extend the use phase of products. The difference between hot-dip galvanisation and zinc spraying illustrates this, with the durability of steel increasing from 16 years of service life in seacoast or heavy industry environments for zinc spray to possibly more than 50 years for hot-dip galvanisation. (galvanizeit.org, n.d.)

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Next to extending the durability of the products, the surface treatments allow for aesthetic options for the metal products. Steel and aluminium products can be found in a multitude of different colours, depending on the customers wishes. But these customers are usually unaware of the choices they do not have, such as potentially hazardous products versus safe ones.

SURFACE TREATMENT IMPACTS

Surface treatments impact the recyclability of metals as the health of people dealing with them.

Recylcling impacts

Surface treatments can be removed in various ways but are usually not considered to be a problem for steel and aluminium. (Bonnema, 2019) (Schlesinger, 2014) This is because before melting scrap, the surface treatments are thermodynamically removed. Tramp elements of the surface treatments can make into the alloys however. (Furu, 2010) For both steel (Daehn, 2017) and aluminium, (Gaustad, 2012), the amount of tramp elements is an increasing problem. For the moment dilution with virgin material is the go to solution.

For most metal production processes, an amount of byproduct is created. The beforementioned slags created in the steel- and aluminium-production have applications in the metal industry, but in Europe 42% (18,8 Mt) and 37% (16,7Mt) are used as road base and cement incorporation respectively. (Gomes, 2006) Next to that some slags are still being landfilled. Some of the tramp elements that get into the alloys, may also get lost in the slags. This means valuable and possibly harmful elements end up in the environment.

Health impacts

It is not often a subject of discussion, or even part of our awareness, but every time our skin touches a material, chemicals are exchanged. The skin absorbs certain molecules, or tiny particles from a product release and embed themselves in our skin, leaking whatever chemicals they contain. As long as the amount of chemicals that rub off on our skin is uncertain, it is difficult to estimate, or evaluate the health risks related to this type of exposure.

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As an example, the azo dyes used in anodization of aluminium contain aromatic ring in their chemical structure. Cleavage products of these structures can be carcinogenic. A study was performed for azo dyes in tattoo bands, folders of paper, toys, bed clothes, watch straps and inks. All were found to have higher than negligible values of carcinogens, (Zeilmaker, 2000) and some exceeded the maximum permissible level. These products have a likely scenario of skin contact during the use phase. A similar study for metal products using this type of dyes has not been performed, and many metal products are not considered to be in regular contact with human skin. With aluminium becoming a greater part of our daily lives in products such as phones, laptops, but also door handles and thermos bottles, skin contact is becoming more plentiful.

Next to direct skin contact, every material ‘sheds or emits’ particles, molecules or atoms from its surface. In relation to our health, Volatile Organic Compounds (VOCs) have become the focus of many studies. (McDonald B. C., 2018) And while the detrimental impact of these molecules is starting to become public knowledge, the effects of other abrading materials are not. It is known that products like the tires of a car shed large amounts of rubber on the road surfaces, expelling all kinds of toxic chemicals into the environment. But little is known about the shedding of fine particles of metal products in our homes, offices or outside.

These health risks have to do with how we use our products, but there are also severe health issues concerning metal production. Companies in metal recycling have mentioned problems with improperly sorted scrap resulting in possibly toxic fumes during the melting process. A 2016 study on Electric Arc Furnace workers showed an increase in deaths due to lung cancer. (Cappelletti, 2016) Companies that engage in recycling have confirmed that surface treatments and excess material on scrap metal (coatings, polymers, zinc layers etc.) are removed during heating, turning either into gas or dust. (Bonnema, 2019)

In February 2019, the municipality of Tilburg and the Nederlandse Spoorwegen decided to compensate laborers who were exposed to chromium 6 (hexavalent chromium). (Nederlandse Omproep Stichting, 2019) Laborers had to remove paint containing the carcinogenic chromium, or were exposed to the airborne particles resulting from this work. Internationally, there is a growing concern about fine dust, VOC’s and other airborne pollutants. (McDonald B. C., 2018) With the health risks becoming a more public matter, and with the public awakening to the issues, companies should look to solve these problems proactively.

In countries like the Netherlands, emission standards are comparatively strict. Which is one of the reasons why the country itself does not process a lot of the scrap that doesn’t meet its requirements (no surface treatments, oils, polymers etc.). As mentioned in the ‘Processing’ paragraph, these surface treatments and contaminations can be removed through a heating process before melting the scrap. But since not all of these processes take place in a sealed chamber, emissions with possibly toxic chemicals from surface treatments and contaminants can occur. This is why scrap that doesn’t meet requirements is exported to places where they

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either do have the proper equipment, or emission standards are not as high. (Overduin, 2010) Unavoidable health risks are therefore relocated instead of treated.

A study in 2000 showed that BF slag leaches heavy metals like chromium, lead and vanadium into its surroundings. Copper slag contains even higher amounts of leaching lead, nickel and arsenic. (Tossavainen, 2000) Unless steps are taken to assure these elements do not make it into the metal and/or slags, it is really irresponsible to put this material in places where they may be both a health- and environmental hazard.

CIRCULAR PERSPECTIVES

Within the Cradle to Cradle concept, every atom, molecule, particle is considered a nutrient. It is valuable to either organisms, nutrient cycles or e.g. top soil in the biosphere (consumption products) ór it is valuable as a technical nutrient in continuous cycles of use, reuse and recycling in the technosphere (service products). To simplify this complex model, two nutrient cycles are defined; a technical- and a biological cycle. Products and materials can be characterized and optimized to being part of either of these two. Some products contain components that belong in both cycles. The key there is to be able to separate these components in the recycling process.

Biological Cycle

The biological cycle describes consumption products that directly or eventually enter the biosphere during or after use. Examples of these are for instance food, cleaning products, but also the outer layer of a car tire (through abrasion). These products are consumed or used up during use and their materials enter the biosphere (air, soil or water). Some products that are part of the biological cycle can be cascaded several times before being released into the biosphere. Paper is such an example. After a maximum of 7 cycles, the paper fibers are too short to be recycled again. The resulting pulp should be safe to re-enter the biosphere as a nutrient through composting or incineration. The goal of the cascade is to 'buy time' for new biomass to grow new fibers.

Many bio- ánd technosphere products are currently being incinerated at the end of their use phase, or after a process of downcycling steps. Unfortunately, almost none of those products were initially designed for this purpose, creating unwanted side effect such as air pollution and resource scarcity. A good example are car tires. The outer layer abrades against the road surface, leaving behind tiny rubber particles. These particles find their way into the soil, our waters and our lungs. However, car tires were never designed to be bio-degradable, water-

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soluble or safe for human lungs. In 2016, big turmoil arose in the Netherlands following studies that showed adverse health effects for (young) soccer players after being exposed to car tire particles that were downcycled into pellets for artificial grass pitches. The studies showed that the pellets contained among other things potentially carcinogenic chemicals. (Marsili, 2014) Many football clubs decided to get rid of their artificial pitches and return to real grass. The RIVM in the Netherlands performed a study of the soil surrounding some of these pitches with rubber granulate. The soil was found to be contaminated. (Verschoor, 2018)

Car tires are not designed for their fate which is abrasion into the biosphere. Unfortunately, the same holds true for many products in use today. Our challenge is to define and optimize materials for their intended use and recycling pathways.

Technical cycle

The technical cycle contains products and materials that provide a service and that can be recovered and recycled without loss of quality. If a product or material is re-used, or remanufactured after the first use phase, this is generally called recycling. In most cases however there is loss of quality, or contamination of materials. This is called **down**cycling: After several recycling the materials still end up being either incinerated landfilled or worse.

Many metal products are being recycled in technical cycles. However, due to the use of e.g. undefined recycling inputs and non-optimized surface treatments this process still leads to air pollution, health risks for people and the environment and waste.

The next chapter provides an outlook on solutions as we move from conventional recycling to a circular economy, where materials keep their value and waste no longer exists.

OUTLOOK ON SOLUTIONS

The mining of virgin metal is still a necessity at this point, since mixing it in with recycled scrap is the only commercially applied way of reaching the desired compositions. (Bjorkman, 2014) Players in the steel and aluminium recycling industry have confirmed this. (Loven, 2019) (Bonnema, 2019) For the steel industry, copper contamination is the biggest issue. (Daehn, 2017) But it can be countered by adding virgin steel to the melt. For aluminium,

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issues may arise from copper, tin, lead and lithium contamination. The same principle of adding in virgin material to create the desired composition is applied. (Loven, 2019)

This approach only works if virgin metals are available, which depends on geological reserves as well as political relations since not all countries have natural stores of metal ores. To create stable use of metals in the future ensuring availability, a higher quality of recycling is required. Nutrient shortage is already showing in the field of rare earth elements, in which China is responsible for the mining of 93%. (Than, 2018) With the immense volumes and the longevity of metals in the built environment, this group of products will become the material banks for the needs of the industry in the future.

With the amount of metal used increasing, so increases the amount of recycled metal. The alloys used are contaminated with nutrients that can serve better purposes. Instead of loading the alloys with contaminated scrap to save money, how about extracting the nutrients, so they can be applied in an optimized scenario. If excess copper could be taken from a steel alloy, it could be applied where it is mostly needed, in for instance electrical wiring. Another possible optimization could be to develop surface treatments which can be easily removed and recycled, extracting the very nutrients needed for the surface treatment of a new product.

But we could even go one step further. How about designing metal products with surface treatments that actually improve the environment or benefit the people using them. One example of that might be to have surface treatments that bind fine dust.

Our conventional approach has yielded some recycling methods and designs that show the potential of proper metal use. The amount of waste is reduced by increasing the percentages of recycled metal over all industries. This increase in efficiency is sorely needed to stop the wasteful loss of valuable nutrients. But it is not enough! An increase in efficiency can only ever result in postponing the depletion of nutrients, and the pollution of our products and environments with unwanted elements.

To create a completely healthy circular system, the metals industry needs to look at its products in full, with all the potentials of each element that is used. Keep supporting creativity, and a desire to search past the 20 ways in which improvement isn't possible, for that one way in which it is!

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