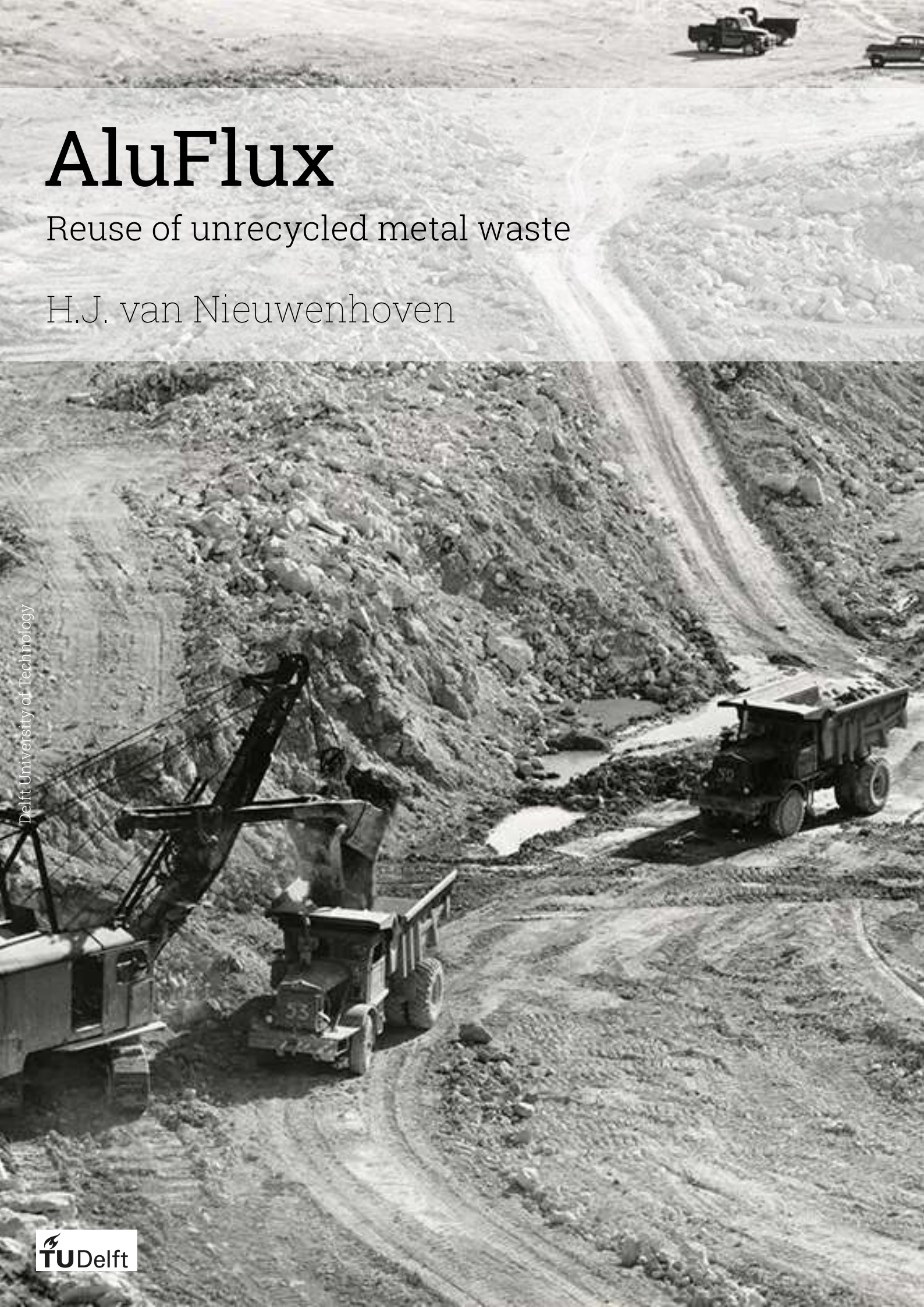
AluFlux

Reuse of unrecycled metal waste

H.J. van Nieuwenhoven



Delft University of Technology

TU Delft

AluFlux

Reuse of unrecycled metal waste

by

H.J. van Nieuwenhoven

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday, June 17th, 2025 at 10:45.

Student number:	5008948	
Project duration:	November, 2024 – June, 2025	
Thesis committee:	Dr. ir. T. Bristogianni,	TU Delft, supervisor
	Dr. ir. M. Bilow,	TU Delft

Cover: ”Line of dump trucks being loaded with bauxite ore in an open pit in Saline County” (Alancaster, 2024)

An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft

Acknowledgements

You have before you the final report of my thesis. Among all the people who taught, helped and supported me, I would like to give special thanks and appreciations to some people who have supported me along the way.

First of all, Telesilla Bristogianni, my first mentor for this project. I am deeply grateful for the trust in the project and the courage to supervise a thesis project outside of her field of work.

Secondly, I would like to thank Marcel Bilow for his support and for seeing the value in a project dominated by material science. Throughout the project Marcel had a guiding role and helped overseeing the larger picture.

Special thanks to Yan Ma for his support support and providing insights as an informal external advisor from the department of Material Science in the Faculty of Mechanical Engineering. He showed genuine interest in the project and took the time to answer even the most basic questions.

Thanks to Ron and Richard for helping around in the in the Stevin lab.

Finally, I would like to thank Malou, for supporting me throughout the project.

H.J. van Nieuwenhoven
Delft, June 2025

Abstract

Reducing waste production is key to achieving a circular economy. The European metal industry consumes over 1.2 billion TJ of energy every year. This number could be reduced by reusing material that is currently being wasted.

The current problem is that the recycling industry focuses on creating clean secondary raw materials from waste. This means that large quantities of material are rejected because they are too contaminated to meet these high standards, or because it is not economically viable to recycle them. This thesis focuses on the value of metal waste materials and their potential in architectural applications. By lowering recycling standards and taking a multidisciplinary approach, an integrated process can be developed that can handle a wider range of materials.

Using a powder metallurgical approach, aluminium composite foils are researched for their potential in architectural applications. The material is granulated, compressed and heated to study its behaviour. The best results were obtained using the highest pressure and a heating temperature of 750°C.

These experiments demonstrate that these materials still have considerable value and quality. The material's aesthetic quality is particularly high, making it an excellent material for visual applications. The material's mechanical properties are also interesting for more technical architectural applications.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
Al	Aluminium
ASTM	American Society for Testing and Materials
Cu	Coper
APC	Aluminium polymer composites
CR	Old scrap collection rate
EOL	End-of-life
EOL-RR	End-of-life recycling rate
EU	European Union
FTIR	Fourier transform infrared spectrometer
GPa	Giga pascal
Mg	Magnesium
MIM	Metal injection moulding
Mn	Manganese
MMt	Metric mega tons
MPa	Mega pascal
Mt	Mega tons
OSR	Old scrap ratio
PBT	Polybutylene terephthalate
PE	Polyethylene
PET	Polyethylene terephthalate
PM	Powder metallurgy
PP	Polypropylene
PVC	Polyvinyl chloride
RC	Recycled content
RER	Recycling efficiency rate
Si	Silicon
XRD	X-ray diffraction
XRF	X-ray fluorescence
Zn	Zinc

Mining of sulfur from a deposit at the edge of Ijen's crater lake, Indonesia. Photograph by Aditya Suseno (Suseno, 2015)

1

Introduction

. *“Making trash from trash, prevents it from being wasted.”*

Context

In search of methods to waste less and reuse more, this research sheds light on current state-of-the-art recycling techniques, waste streams, and searches for methods to reduce material going to waste.

What is waste?

To give this thesis an outline it is important to get a clear understanding of the term 'Waste'. Hebel et al., 2014 describes waste as 'unwanted or undesired materials'. This includes man-made materials as well as natural matter. In this research 'waste' will refer to solid waste and not to the contrasting waste produced in the form of radiation or energy. However, to outline the problem in metal production, there will be notes about energy going to waste. i.e. being wasted. The main challenge for our society (in the western world) is how to minimize our production of waste and if materials go unavoidably to waste and how to convert them into a new resource. This is the basis of a circular society.

In search for materials contributing to a more circular economy it is important to also improve the recyclability of these materials.

Metals

Metals are ideal for a circular economy as they can be recycled repeatedly without losing quality during this process. This is however only applicable when the material is properly collected and recycled. Otherwise, secondary metals will face downcycling and quality issues will occur.

The metal production industry in Europe consumes over 120.000 TJ of energy and processes 532 MMT of raw material annually (Eurostat, 2023c). Less than 0.15% of this energy is from renewable sources or biofuels (Eurostat, 2023a). Furthermore, the production industry is responsible for generating more than 77.676 MMt of CO_2 emissions (Eurostat, 2023b). This significant environmental footprint highlights the importance of exploring sustainable practices, such as urban mining and improved recycling or reprocessing techniques to reduce metal going to waste.

Climate change is considered the biggest motivator behind the circular economy (Van Langen et al., 2021). The metal industry is not only a big consumer of energy and producer of CO_2, the industry also brings chemical pollution from processing raw ores. A great example is red mud, also known as bauxite residue (Gura, 2010). Besides, mineral ores are an exhaustible source. The process of retrieving raw material from ores is becoming more intensive and sources are becoming increasingly harder to reach. Also, most mines supplying critical material are not located in the European Union (EU) (European Commission and Directorate-General for Internal Market Industry Entrepreneurship and SMEs et al., 2023). This creates dependence on foreign sources. For example, 63% of our annual bauxite originates from Guinea, which is marked as a country with low governance by the EU. To ensure future production and maintain and support economic growth, it is necessary to develop new techniques to become less dependent on non-European sources.

Recycled material has, as a source, a higher quality than mineral ores. On top of that, recycled materials have already been processed and purified; therefore, it takes less energy to reprocess them to become new material (Khan et al., 2022).

Critical material act

The previous section described dependence on European Union external sources as a motivator for the recycling of metal. This statement is backed

by the European Union Critical Raw Material Act. This act sets benchmarks by 2030 for strategic raw materials and for supply diversification ("Regulation (EU) 2024/1252 Of the european parliament and of the council", 2024). This critical material act distinguishes a list of materials that a considered to be critical. For these materials, the EU has set the following regulations on supply origin by 2030:

- At least 10% of the EU's annual consumption for extraction
- At least 40% of the EU's annual consumption for processing
- At least 25% of the EU's annual consumption for recycling
- No more than 65% of the EU's annual consumption from a single third country becoming more circular increase the chance of meeting these regulations.

Figure 1.1 shows a periodic table highlighting all materials marked as critical and strategic raw material by the EU.

Research hypothesis

While the recycling industry is focusing on redeeming pure materials from metal waste, this research will focus on creating new material from metal waste. Where current processes focus on refinery of metals, resulting in either high energy consumption, use of harmful chemicals and material losses, this research aims to embrace the mixed waste metal and create new valuable material without the need or lesser of these processes used nowadays. This will result in valuable material design for applications within the architectural context. When designing material and an application side by side will potentially increase the positive outcome of this research.

Research framework

Problem statement

The recycling industry focuses on collecting, sorting and refining metal waste streams so they can be used as secondary raw materials. In this process the least contaminated, most refined metal waste is considered as most valuable. On the scale of most valuable to least valuable waste streams the sweet spot is logically on the far left of the scale. Somewhere on the scale there is a turning point, where time and costs do not way up to the yield of the recycled material. The waste streams on the right side of this turning point and up being incinerated or landfilled. This is visualized in figure 1.2.

Exploring new purposes for thus far unrecycled metal containing waste streams offers a promising opportunity to find new processing strategies and techniques to create value for wasted materials.

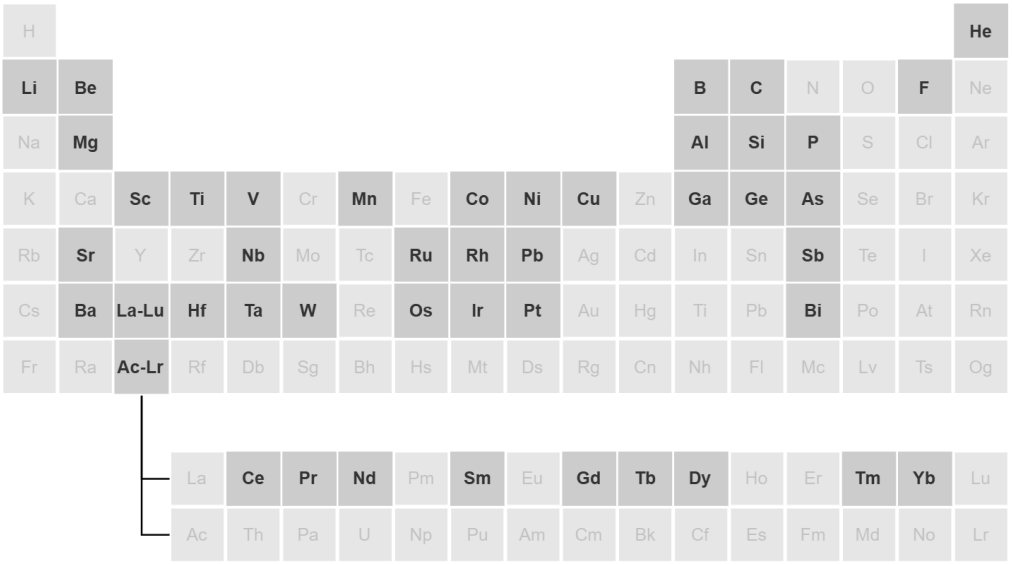
Scientific research gap

However, some experimental research is conducted by for example Al Mahmood et al., 2020 or Cervantes-Reyes et al., 2015. There is a gap in research on experimental methods of recycling metal waste that is thus far too expensive or complicated to be recycled as raw material. Also, current research describes techniques to separate materials. The research does not focus on synergy between materials.

Research questions

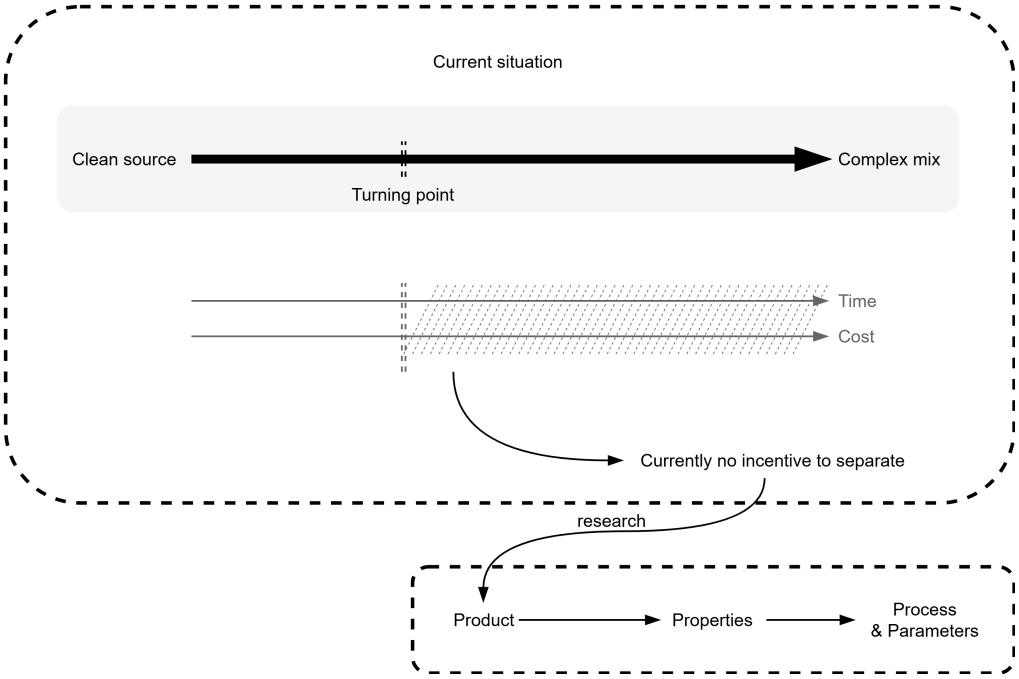
The main research question driving this thesis is: "How can unrecycled, contaminated, mixed metal waste be reprocessed into new materials for architectural applications?"

Figure 1.1: *Critical and strategical materials defined by the EU CRM act.*



Note: The figure shows an overview of the critical and strategical materials defined in the EU CRM act. “Regulation (EU) 2024/1252 Of the european parliament and of the council” (2024).

Figure 1.2: *Problemstatement and research gap*



Note: Schematic overview of problem statement and research gap.

The main research question will be answered by answering the following sub questions:

- What is the current state of metal recycling in Europe, what difficulties are faced, and which waste streams stay unrecycled?
- What are the parameters for processing contaminated metal waste and how do they influence mechanical properties of the material?
- What are potential architectural applications for these parameters and mechanical properties, and aesthetic qualities?

Scope

Source

Waste will be the main source of material for this research project. To give guidance in the search of waste, material that is being co-incinerated or landfilled will be considered as undesired material i.e., waste. Also, material being non-functionally recycled at their end-of-life phase will be considered as waste. Only material undergoing these processes within Europe are included. This concept will be elaborated on in section 1.

Material focus

As described in the introduction, metals are highly suitable for a circular economy. However, production of ore-based material brings a lot of pressure on the environment. There for, this research will focus on metals. Specifically, on considered as critical, non-ferrous metals. However, it should be said that depending on literature and experimentation results different ‘by-materials’ could be involved.

Application focus

To be defined; from material experimentation, preferably visible architectural components. Where the recycled content of the material can show its characteristic.

Based on structural quality of experiment samples examples could be, doorknob, light shade, doorstep, ventilation duct, cable gutters, roofing sheets, vapour barriers, reflective solar shades.

Objectives

The objective in this research is creating value for wasted materials. By doing so high-grade material can be used for a more efficient purpose. Also, this will create a closer to closed loop which helps in the quest to a circular economy.

Ethical considerations

A lot of metal scraps are shipped to foreign countries. The metal scrap is processed under circumstances that would be unacceptable in Europe. This in combination with lower cost of labour will increases the economical viability of the recycling of the metal. Although labour circumstances are often very low, this process benefits the circular economy. It is however questionable whether the cost (not in money) outweigh the benefits. Besides labour circumstances, also some recycling techniques are not performed in Europe due to environmental impact. These techniques are however performed in foreign countries, often in uncontrolled environments resulting in pollution. Theoretically this also benefits the circular economy, for some materials, but results in pollution. This was the basis for China to ban solid waste imports (Lin et al., 2023). This being said, measuring and validating the recycling efficiency, environmental harm and labour circumstances is a very complicated process (Graedel et al., 2011). Therefore, the decision is made for this research that exported waste streams will not be included in this research.

Societal relevance

By creating value for other, now considered as waste materials these materials can be saved from being wasted. By creating a purpose for wasted materials the assumption is made that there will be an incentive for collection and processing in society of this waste. A great example of creating value is the recent deposit on soda cans in the Netherlands. By creating an almost ‘virtual’ value for soda cans the material in these cans is being able to be recycled in a very efficient and specific process.

In an optimal, circular, situation there is very little to no material to recovered. However, up until this day, the most amount of metal scrap end-of-life metal is recycled, or even worse, incinerated. Even though the recycling step is very low on the 9R-ladder (Potting et al., 2017), the impact of this research can be considerably high.

The relevance of this thesis extends beyond the context of waste metals and creates a framework for researching other waste materials for architectural or other purposes. Creating awareness of the complexity of modern materials and minimal recycling solutions is crucial to reduce waste production. Recycling is not the answer to consumption and recyclability in theory is different than recyclability in practice. Resource scarcity in the form of critical materials and climate crisis are both addressed.

This thesis contributes to the broader field of materials science and environmental engineering by exploring new recycling methods and correlating material processing to properties. It encourages further investigation into material properties, the technologies involved in recycling, and the potential environmental benefits of recycling complex or low-value materials.

2

Methodology

Literature research

The literature research is split up in three main parts. In the first part will focus on mapping metal waste streams in the European context. This section includes a general framework for material flow as well as metrics on material flow in Europe. Secondly, the main processes for recycling metal waste in the European context will be mapped and specific waste and recycling residue will be selected for further investigation. The last part of the literature review will focus on metal manufacturing techniques. This part of the literature review will later, in the experimental phase of the research, support the processing of the metal waste to create new material for architectural purposes. The literature research workflow is shown in figure 2.1.

Material selection

Most materials entering the recycling stream will be applicable to this research. However, some other criteria are important to consider when selecting a waste stream for the experimental testing. Waste streams being assessed are provided by manufacturers and recycling companies and from the literature review. The workflow in figure 4.1 shows how a waste stream is assessed for suitability for experimentation and testing.

Material experimentation & testing

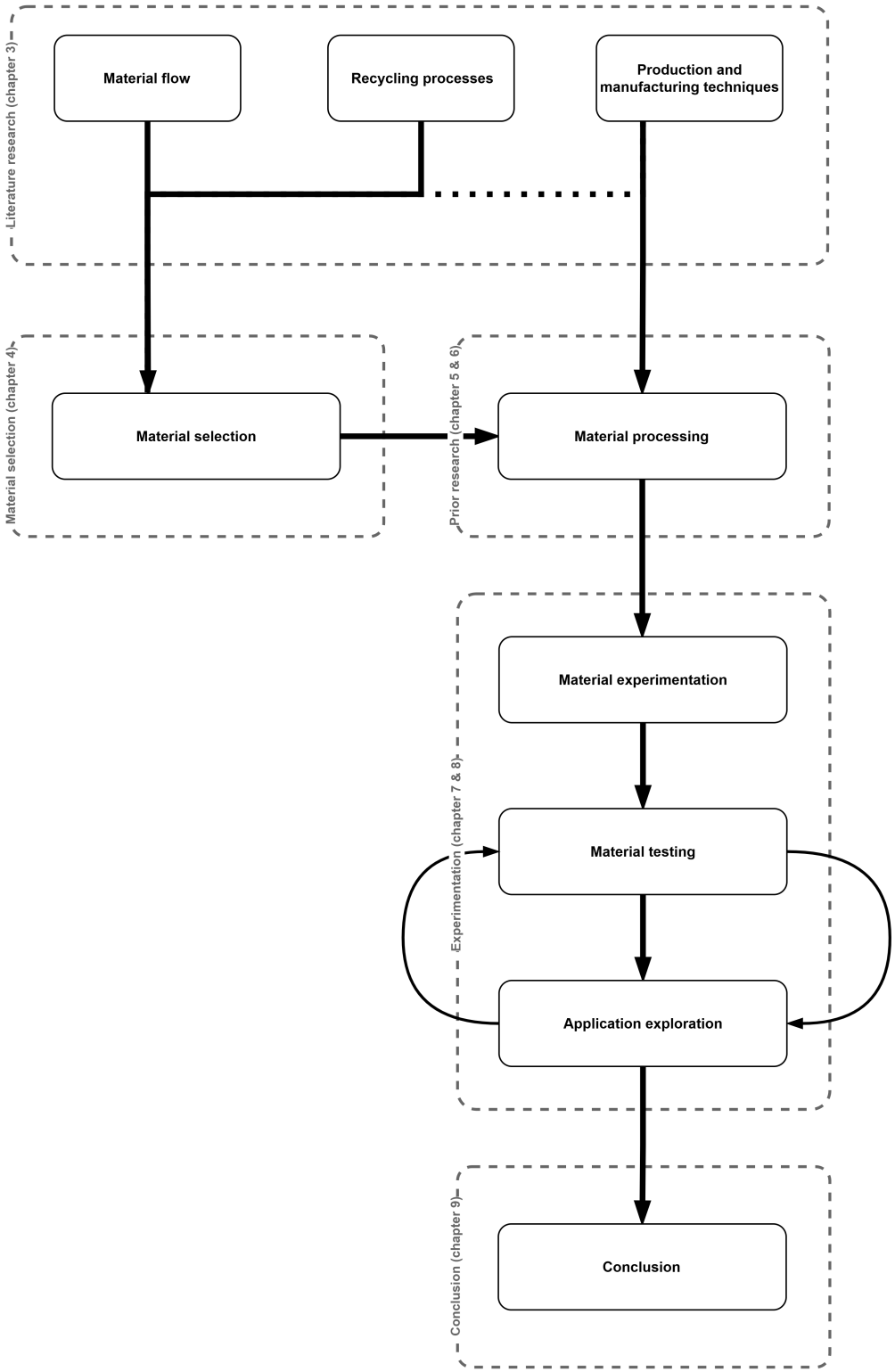
Metal containing waste will be collected and tested in the laboratory. Different metal forming techniques will be conducted to test possibly new material forming.

The newly formed material will be tested for example in a flexural strength test. Further testing will be conducted depending on the purpose of the material design. Moister resistance, corrosion, and oxidation resistance could be considered for further testing. But also, insulative, acoustic, reflective characteristics could be part of further testing.

Research flow

A general overview of the research flow is shown in figure 2.1.

Figure 2.1: *Research flow*



Note: Research flow

Aluminium scrap recycling. Photograph by unknown author (Aluminium, 2022)

3

Literature research

.

Circular strategy

The 9R-ladder in figure 3.1 shows a set of strategies to come to a circular economy (Potting et al., 2017).

When looking at figure 3.1. Design decisions made on a 'high' level on the ladder will have lasting effects on the material life cycles. These choices highly effect the effectiveness of the application of the 'lower' strategies at the end-of-life (EOL) phase of the product. However, these strategies are effective for newly produces products, due to the delay between production and EOL of products (Van Schaik & Reuter, 2004), most available waste products are not designed with these strategies in mind.

This research focuses on the lowest levels of the 9R-ladder. Even though R9 (*Recover*) is a circular strategy contributing to a circular economy, for this research the strategy is considered as disposal and a waste. Schneider and Ragossnig, 2015 and Verhoef et al., 2000, discusses this in further detail. This choice is made because proving and measuring the effect of the recovering strategy compared to recycling is very complex.

Material flow

When a product is completed and leaves manufacturing, it enters the market. With this the first phase starts and the product becomes part of the recycle stock. At a certain moment the product is no longer wanted for any reason and becomes logically unwanted. This is called the end-of-life (EOL) phase. The product gets sorted and separated and becomes part of the recycling process. With this, it enters a new life cycle. This cycle doesn't have a break, that's why it's also referred to as a 'closed-loop' cycle.

However theoretically possible, life cycles of materials are often not a 'closed-loop' life cycle, therefore they a referred to as 'open-loop' cycle. This phenomenon occurs when for example a product is not collected properly in a recycling stream to recover its materials but is discarded to landfill or co-incineration (Khan et al., 2022). Figure 3.2 illustrates a schematic material flow scheme.

Metal

Metals are, generally speaking, retrieved from mined ores. These ores are removed from the ground using heavy machinery, explosives, or manual techniques and transported to a processing facility. The ore is crushed and ground to smaller pieces. Different techniques are used to enrich the metallic content of the ore material. After this process the ore is smelted and refined. If applicable, electrolysis processes are used to further purify for high-quality metals.

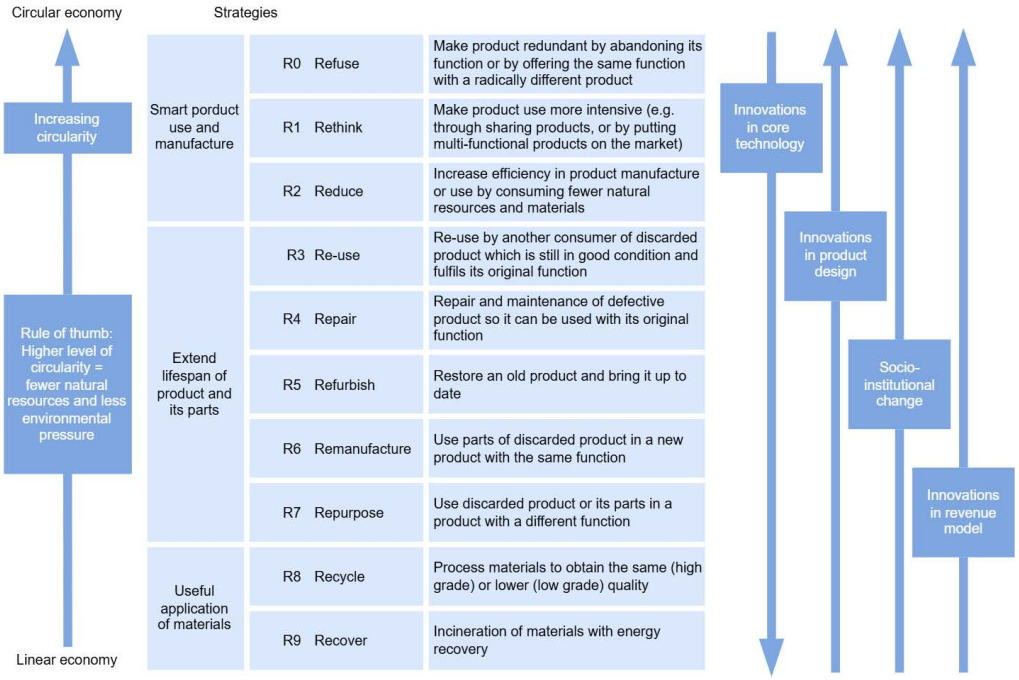
In the metal industry there is a distinction between primary raw material and secondary raw material. Primary raw material is new, ore-based material. This material originates often from mines. Secondary raw material is material originating from all other streams than the primary raw material (Themelis, 2018).

Metal types can be divided into two families: *ferrous metals* and *non-ferrous metals*. Non-ferrous metals consist of aluminium, copper, zinc, titanium, tin, lead, chromium, brass, gold, platinum, silver, and palladium. Ferrous metals are mainly alloy steel, carbon steel, cast iron and wrought iron (Khan et al., 2022; Themelis, 2018).

Manufacturing

The section below describes different forming and joining techniques. The forming techniques are described from general 'rough' techniques to more refined specific techniques. The joining techniques are described in no particular

Figure 3.1: *9R-strategy ladder*



Note: The figure shows an overview of the 9R strategies ((Potting et al., 2017)).

order.

Forming techniques

The following metal forming techniques are described in the section bellow: *Forging, rolling, extruding, casting, machining, powder metallurgy, metal injection moulding.*

Forging

When forging, the metal gets heated until it becomes soft, but not fluid. With a hammer or a hammering machine the metal gets formed in the desired shape.

Rolling

The metal is rolled through dies in the desired shape. This can be done either 'hot' or 'cold'. Both processes lead to different material properties.

Extruding

The metal is pushed through an opening in the desired shape. Theoretically elements of infinite length can be produced.

Casting

The metal gets heated to its melting point and generally poured into a mould. This mould can be made of sand (sand casting) or another material.

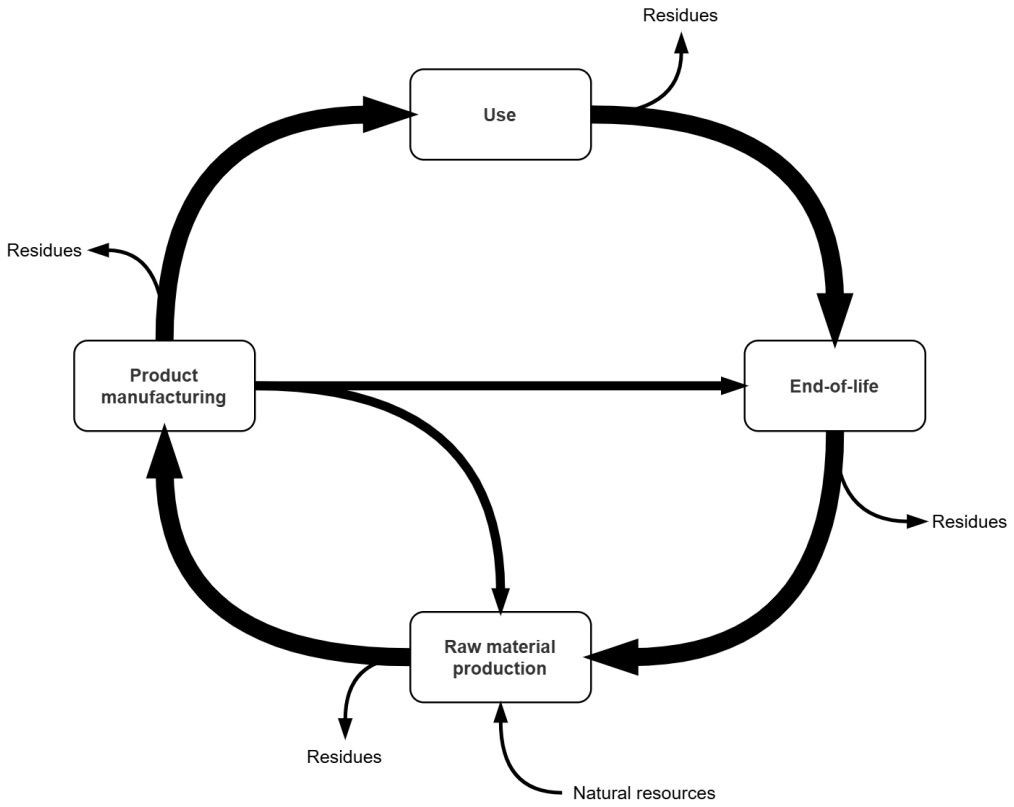
Machining

The metal gets cut using a range of tools. Different machines are milling machines, lathe machines and grinding machines.

The following parameters are used to assess the machining and machinability of a metal: tool life, cutting force, surface finish, and chip formation.

The tool life is the service life of the cutting tool until the point the tool is no

Figure 3.2: *Schematic overview of a typical process of material shredder into different material categories.*



Note: The figure shows a general overview of a typical recycling process of mixed metal waste. Björkman and Samuelsson (2014).

longer usable due to wear. The surface quality can be a criteria for a product if the surface is not handled any further after machining. The quality depends on the cutting parameters and the geometry of the cutting edge of the tool. The chip formation is not necessarily of importance to the product itself but more to the production process. If a large volume of chips form in restricted area, this can be an obstacle (Buschow, 2001a).

In the process of machining the surface of the machined material can reach high temperatures, this should be taken into consideration during the production process.

Powder metallurgy (PM) and Metal injection moulding (MIM)

These forming methods rely on making a powder, generally out of different metals. This creates a unique mixture of metals that cannot be obtained from melting or other methods.

For PM the powder is brought into a cavity in the desired shape of the product. A die press presses with high force on the powder. Under the high pressure the molecules create bonds. The ‘green’ part is created. After this the element is sintered at a specific temperature. It is important that this temperature is high enough to create bonds, but without melting the element. The powder used in

PM is usually in the range of 50-100 µm.

MIM relies on the same technique. However, in MIM the powder is injected under high pressure in a mould. There is no need for a die press to create the green element. After this the binder is debound from the green part, this results in the brown part. The brown part is sintered, and the finished part is created. MIM elements shrink throughout their processing. MIM powder is usually smaller than PM powder and ranges from 2-15 µm (Buschow, 2001b).

Assembly techniques

Metal joining is a fundamental process in manufacturing. It involves the joining of two pieces of metal to one joined element. The preferred joining technique is based on different factors such a temperature, corrosion, composition, etc. In this section the following joining techniques will be briefly discusses: *fusing*, *soldering*, *adhesives*, and *mechanical fastening*.

Fusing

Fusing is joining two the same materials with or without a filler material. This is also referred to as welding. The two joining surfaces are brought to their melting point and fused together. This can be done either with or without a filler material. For other some materials (e.g. plastics) it is also possible to chemically melt them without introducing heat. If performed well a welded joined is as strong as the rest of the joined material (American Welding Society, 2020).

Soldering

Soldering is joining two the same, or different materials with a filler material non-similar to either of the joining surfaces. The key aspect of soldering is that the to be joined material does not melt. Only the filler material melts and flows between the two surfaces. The created joint is weaker than welded joints. In terminology there is a difference between the temperature at which the soldering is to be performed. Soldering is done until a temperature of 450°C, above 450°C it is called brazing. From further on in this thesis there will be referred to thesis processes in these terms. In terms of production process and different materials being involved it can be practical to use both soldering and brazing to prevent unwanted melting of material (American Welding Society, 2020).

Adhesive

Adhesive bonds between materials are made using synthetic resins which solidify. Although physical phenomena are technically the same as with soldering and brazing, the three processes differ in their application a metallurgic effect and are to be considered as different joining techniques. Adhesive bonding creates a weaker joint compared to welding, brazing and soldering. Also, it may degrade under high temperatures (American Welding Society, 2020; Lancaster, 1980).

Mechanical fastening

Mechanical fastening can be done with different fasteners: bolt, rivets, screw, or clamps for example. Some types of mechanical fastening create a non-permanent bond. This eases the disassemble process of a product. A disadvantage of mechanical fastening is that it adds weight to the assembly. Also, mechanical fastening usually creates a non-equal stress distribution across the joining surfaces.

Metal Recycling

'Keep in mind that recycling is nothing more than separating based on given criteria.'

Metal scrap

In the metal recycling industry three main types of metal waste are defined: *home scrap*, *pre-consumer (or new, or industrial) scrap* and *post-consumer (or old) scrap* (Graedel et al., 2011).

Home scrap
Home scrap is material that comes directly from the metal production industry, e.g. from furnace surroundings, from ladles, slags, offcut pieces during treatment, etc. This scrap is well sorted in specific qualities and often recycled and remelted within the plant. This is possible because the composition of the material is known and if handled with care has very minimal impurities.

Pre-consumer scrap
Pre-consumer scrap originates from the fabrication or manufacturing process. In contrary to home scrap, pre-consumer scrap is not recycled within the same facility but is collected and transferred to the scrap market. Because of its known properties, high purity, and value, its recycling is generally economically beneficial and easy to accomplish, although recycling becomes more difficult the closer one gets to finished products (e.g., rejected printed circuit boards).

Post-consumer scrap
Post-consumer scrap is metal in product that reached their EOL phase. The recycling of post-consumer scrap requires considerably more effort, specific knowledge and specialty equipment, particularly when the fragments of metal are relatively small (Björkman & Samuelsson, 2014; Graedel et al., 2011; Smil, 2016).

With more figurative distance from the raw material production the recycling of the metal waste becomes harder and more intensive. Dependent on the type of metal it is highly important to keep waste streams separated to reduce contamination of the metal waste stream.

Functional and Non-Functional recycling
For this research it is important to have a clear understanding of two forms of recycling. Graedel et al., 2011 Describes the following forms of recycling: functional recycling and non-functional recycling.

Functional recycling
Functional recycling is the part of end-of-life recycling where the metal in collected waste products is sorted and separated to recover recyclates that contribute to the secondary raw material production. This means the recyclates are recovered to be metal or metal alloys. Often the secondary raw material produced from the recyclates is not the same alloy, but any alloy within a class of alloys. Afterwards, the alloy composition will by adjusted by adding reagents or primary raw material to obtain the desired alloy grade.

Non-functional recycling
Non-functional recycling is the other part of end-of-life recycling where metal is not sorted and separated, or only to a certain extent. The metal is collected as old scrap metal and only sorted in a similar large-magnitude metal stream as a ‘tramp’ or impurity element. This prevents the material from being dissipated, but the metals functionality is going to waste. The metal ‘disappears’ in the metal stream, its generally impossible to recover the metal from this metal stream. Even though, technically speaking, non-functional recycling is type of recycling. It results in an open-life cycle, as discussed in section material flow.

Recycling statistics
In Europe 88 MMT is being recycled annually (in 2023). This is 16.5% of the total processed metal ores. At the EOL-phase 6 MMT (75.000 truckloads) of metal is being incinerated and 3 MMT (37.500 truckloads) metal is being landfilled annually. 21 MMT is being exported for outside Europe recycling (Eurostat, 2023c). Statistics on recycling efficiency and circularity of EU external recycling processes are hard to validate,

often the efficiency is low (Graedel et al., 2011).

The Sankey diagram in figure 3.3 shows the material flow for metal ores in Europe. A larger format of this diagram can be found in appendix A.

For this research the proposed framework for recycling statistics by Graedel et al., 2011 is considered. By considering the recycling statistics on different levels, a broader view on the current state of recycling. Often recycling statistics are described only in percentage of the current primary production of raw material, this gives for this research a to narrow approach of insight of the current situation.

The define recycling efficiencies at EOL (collection, process efficiency, recycling rate) and in metal production (recycling input rate, recycled content, old scrap ratio). At EOL, the recycling efficiency of a metal can be measured at three levels:

- The amount of end-of-life metal in discarded products that is collected and enters the recycling chain; *old scrap collection rate (CR)* (eq.1).
- The efficiency of any recycling process; *recycling process efficiency rate* (eq.2).
- The amount of material being functionally recycled, including recycling as pure metal; *end-of-life recycling rate* (eq.3). The opposite of functional EOL-RR is; *non-functional EOL-RR* (eq.4).

This ratio describes the amount of metal being collected but being lost in the recycling process as 'tramp' or impurity element to the dominant metal in the recycling stream. The functional EOL-RR is highly influenced by the weakest link in the recycling process. Typically, this is the collection process (Graedel et al., 2011). Figure 3.4 represents a simplified overview of a metal life cycle, based on which the mentioned above end-of-life metrics can be calculated:

$$\text{Old scrap collation rate (CR)} = \frac{E}{D} \quad (1)$$

$$\text{Recycling efficiency rate (RER)} = \frac{G}{E} \quad (2)$$

$$\text{Functional EOL-RR} = \frac{G}{D} \quad (3)$$

$$\text{Non-functional EOL-RR} = \frac{F}{D} \quad (4)$$

In the production of metal two extra metrics are important: *the recycled content (RC)* (eq.5) and the *old scrap ratio (OSR)* (eq.6). The RC describes the ratio of secondary raw material in the total input of metal in raw material production. The other part of this ratio is naturally primary raw material.

$$\text{RC} = \frac{J+M}{A+J+M} \quad (5)$$

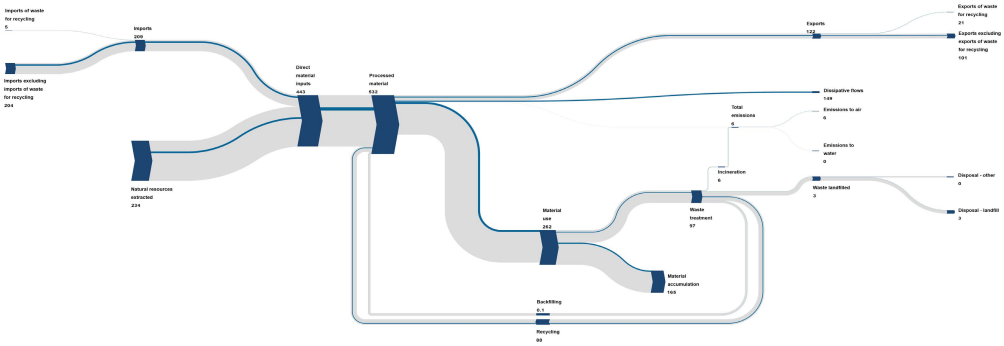
The calculation of the RC ratio is at global level straight forward. However, on European level, let alone, country level near to impossible. This is because the lack of information about material being imported an exported. As scrap metal as well as in use products.

The OSR describes de ratio between recycled material originating from post-consumer waste sources and pre-consumer waste. This ratio is especially interesting because it highlights the underlying metrics corresponding to the RC ratio.

$$\text{OSR} = \frac{G}{G+H} \quad (6)$$

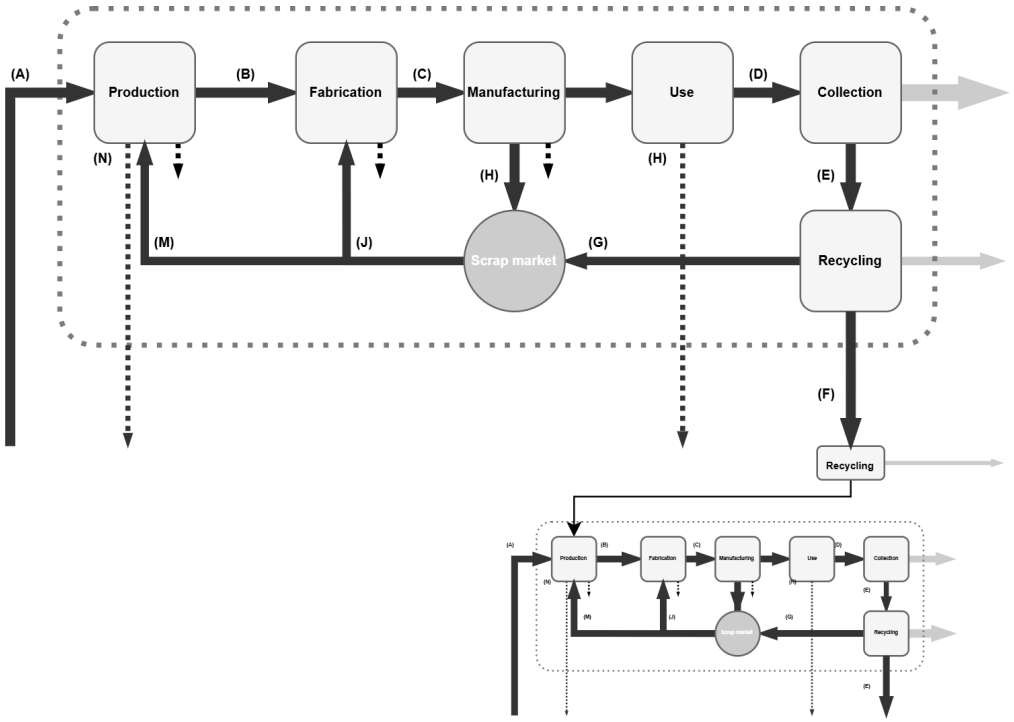
When interpretating these ratios the following factors should be taken into

Figure 3.3: *Material flow diagram, Europe.*



Note: The figure shows a material flow diagram for metal ores in Europe. The mass weight is expressed in MMT (Metric mega tonnes). Eurostat (2023c).

Figure 3.4: *Metal recycling flow and losses.*



Note: Primary metal input (A), Refined metal (B), Intermediate products (e.g. alloys, semis) (C), End-of-life (EOL) products (metal content) (D), End-of-life (EOL) metal collected for recycling (E), End-of-life (EOL) metal separated for non-functional recycling (F), End-of-life (EOL) recycled metal (old scrap) (G), Manufacturing scrap (new scrap) (J), Fabrication scrap (new & old) (M), Production scrap (new & old) (N), In-use dissipation (O), (Björkman & Samuelsson, 2014).

consideration: The recycle content (RC) in metals is dependent on the amount of scrap availability and scrap quality. The amount of pre-consumer waste used in

metal production is dependent on the process efficiency of the fabrication and manufacturing process. The amount of post-consumer waste used in metal production is dependent on the efficiency of collection and recycling process. High metal demands nowadays in combination with the generally long-life span of products (made from these metals) result often in RC ratios much smaller than 100%. Even with a highly efficient collection and recycling system, there would still be insufficient post-consumer waste to achieve both a high recycled content (RC) and a high old scrap ratio (OSR) in this scenario.

Comparing recycling content ratios across different metals poses challenges due to variations in the growth rates of metal demand, differences in end-use applications with distinct lifespans and in-use dissipation rates, diverse production processes that may limit scrap usage, and varying tolerances for impurities in metal production (Van Schaik & Reuter, 2004). Recycling efficiency differs among metals, influenced by the specific processes optimized for particular metals or grades. While efficiency can be high, it will never reach 100% due to thermodynamic constraints and other factors (Castro et al., 2004).

Additionally, recycling efficiency is highly dependent on the specific product. Factors such as whether the metal is used in pure or alloyed form, the concentration of the metal in a product, product design (ease of disassembly), and the economic value of the metal all significantly influence recycling outcomes.

To conclude, for this research a material stream with a high CR ratio and a low RER indicates a potential material for creating value. Also, material streams with a low CR or a high Non-functional EOL-RR are potentially materials for this thesis. However, it must be noted that this would mean a collection program for this material should be initiated. The feasibility of this is doubtful.

The OSR is not used in this research, however it must be emphasized that this flow schedule indicates very clearly that the recycled content in production of metal (or generally speaking for any material) does not show where the secondary material originates from. Theoretically, manufacturers can claim a product consists of 50% recycled material. In case this recycled material originates from their own production facility (home scrap) its discussable how recycled this material actually is.

Recycling, as a practice

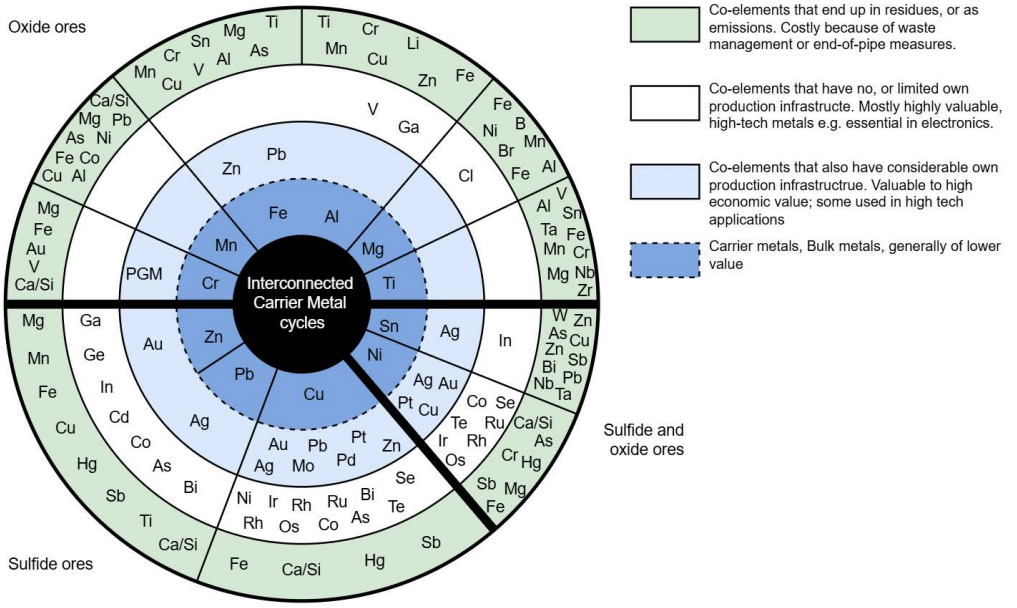
Modern products often consist of a mix of metals that do not naturally occur together in traditional resource systems (figure 3.5) (Reuter et al., 2003). As a result, these materials are not always compatible with existing metal production processes, which were originally designed and optimized for processing primary raw materials, including both primary metals and their naturally associated valuable or hazardous minor elements. This mismatch leads to the generation of complex residual waste streams or unwanted harmful emissions that the current systems cannot effectively manage. Consequently, the recycling and processing of such end-of-life products become challenging, leading to lower recycling rates for these material streams.

Recycling techniques

Figure 3.6 represents the schematic flow of metal recovery from scrap using pyrometallurgy and hydrometallurgy processes (Tuncuk et al., 2012).

Dependent on the quality of waste different approaches to the recycling of metal waste are common. Pre-consumer scrap is often directly recycled internally or send

Figure 3.5: *Links between metals in natural resources*



Note: Linked metals as can be found in natural resources. Legend top to bottom equivalent to rings from outside to inside (Reuter et al., 2003).

to production plants without ending in the waste management and recycling stream (Khan et al., 2022). Post-consumer waste and scrap is collected in recycling plants and get processed appropriately depending on waste characteristics.

Dismantling manually

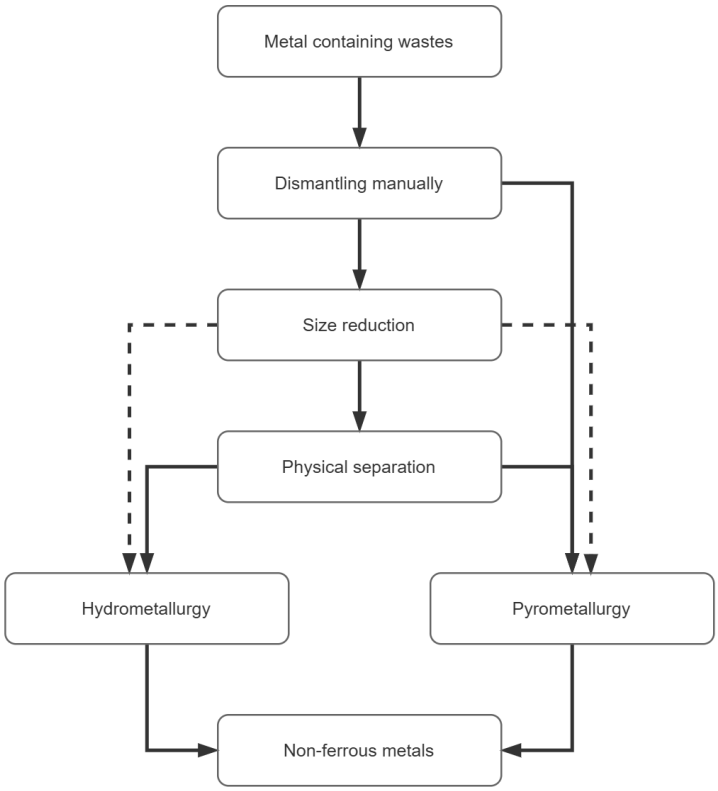
Modern products often consist of a variety of different materials. In an ideal situation these materials should be separated as much as possible before proceeding further recycling steps. However, due to economically being often unattractive products do not get separated or only partially. This leads to contamination in the material that are not compatible with the current metallurgic processes' routes described by Reuter et al., 2003.

Size reduction and physical separation

The system shown in figure 3.7 shows a generic overview of a system to reduce material size and separate the parts based on physical aspects. The scrap material is fed into a shredder, where it is broken down into smaller pieces. Tiny, lightweight particles, primarily composed of organic material, are collected as dust through pneumatic conveyance. Additionally, the shredded material can undergo several separation processes, including magnetic separation, sieving, and air separation. During these steps, most steel is recovered in the magnetic fraction, nonferrous metals are separated into the nonmagnetic fraction, and very small or light particles are removed. Additional separation techniques, such as density separation, weak magnetic separation, eddy current separation, electrostatic separation, manual sorting, or automated sorting based on colour or physical characteristics, may be conducted to enhance sorting efficiency.

Despite these processes, the output from the shredder is often not fully separated. It is common to find mixed fragments containing steel along with copper,

Figure 3.6: *Schematic overview of several extraction processes for metal recovery.*



Note: The figure shows a general overview of a typical recycling process of mixed metal waste (Tuncuk et al., 2012).

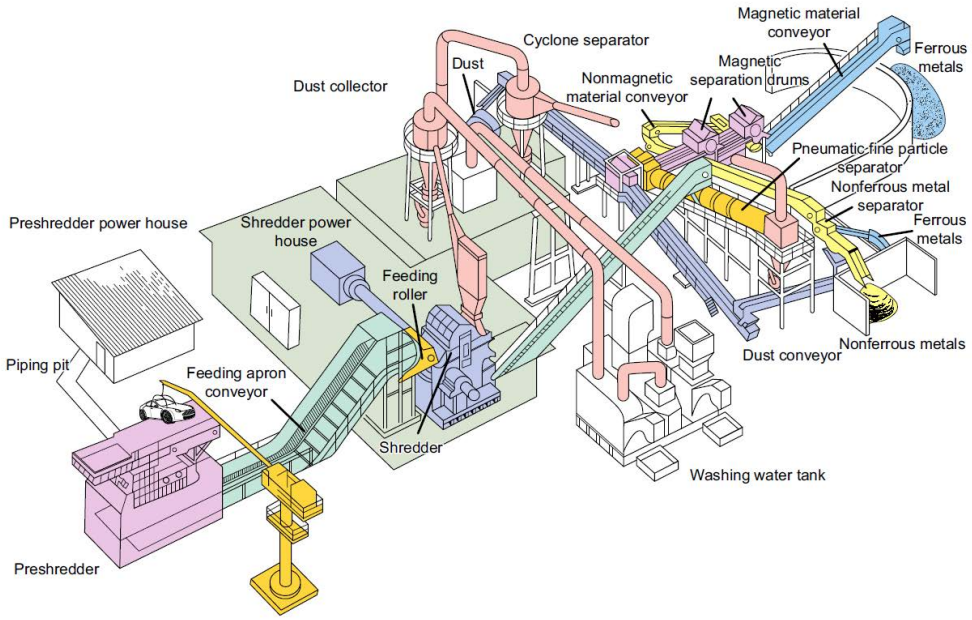
aluminium, or other metals (Reuter et al., 2005; Van Schaik et al., 2002). Depending on the sorting technique and the degree of material liberation during shredding, these mixed pieces may be misclassified into either steel or copper fractions. This issue can also arise due to unsuitable particle sizes for the separation method used. Residual waste from these treatments is typically directed to landfills or incineration (Damgaard et al., 2009).

Pyrometallurgy (smelting)

Pyrometallurgy is widely used for extracting metals from waste, providing an effective solution for recovering metals. These metals often appear in waste as oxides, which must be reduced to recover the metal. This reduction process typically involves heating the waste to temperatures above 1000°C, where the metals are selectively volatilized and condensed afterwards. Pyrometallurgy is a traditional method that generally includes processes like waste incineration, sintering, and high-temperature melting. Common equipment used in industrial pyrometallurgy includes smelting furnaces, thermal reactors, and plasma furnaces (Krishnan et al., 2021).

Contamination in the metal processed with pyrometallurgical methods will lead to material loss or ineffective separation.

Figure 3.7: *Schematic overview of a typical process of material shredder into different material categories.*



Note: The figure shows a general overview of a typical recycling process of mixed metal waste. The metal waste is fed to the shredder and processed in the system (Björkman & Samuelsson, 2014).

Hydrometallurgy (leaching and purification)

Hydrometallurgy uses chemical reactions to dissolve material. This can be done either in aqueous solutions or organic solutions. Steps involved in the hydrometallurgical process are leaching, purification and recovery. The alkaline used in acid-leaching is referred to as the lixiviant. After the metal is dissolved in the leach solution, the solution is 'pregnant'. After purifying the pregnant leach solution, the metal can be recovered using electrolysis, gaseous reduction and precipitation (Krishnan et al., 2021).

Recycling Residue

The recycling residue is considered the part of the waste stream that does not become recycled. For example, when mixed metal waste, copper, steel, aluminium, zinc and plastic is mixed. Eventually there will be a mix of material that is left over. At some point in the recycling process the material didn't get sorted. This means the material didn't belong, based on recycling criteria, somewhere in the recycling batch.

Metal contamination accumulation

Contamination can occur from various sources. A contamination can be considered as a different material than the wanted material from the recycling process. However, some kinds of contamination are wanted. For instance, carbon in steel or zinc in aluminium alloys. For certain types of metal waste contamination is more of importance than in other waste streams. A good example of contamination is a piece of copper, stuck to a steel bracket. The steel bracket will be taken out of the waste stream and be sorted in the ferrous metal container.

However, because the shredding process did not sufficiently separate the copper from the steel. The copper ends up in the steel recycling stream. This will result in different, often negative, changes of property of the secondary raw material (Björkman & Samuelsson, 2014).

For the recycling of steel this is a relatively small problem. During the production process of raw steel most of contamination will either evaporate or be removed in the form of skims or slags. However, for most non-ferrous metals this problem is of a way larger scale (Worldsteel, 2021).

Conclusion

To conclude, the recycling of metal containing waste presents challenges and opportunities. The 9R-ladder discussed above shows the importance of strategic product and material design as these choices have major impact on the recyclability of a product or material at the end-of-life phase. Efficient and effective recycling depends on multiple factors like, collection rate, sorting processes, and the type of metals and materials involved.

4

Material selection

Material criteria

The selection of suitable metal waste material is conducted based on a set of criteria. The criteria set of is based on the in the literature from chapter 3.

The following criteria are defined to enhance feasibility and ensure sustainable and manageable outcomes:

- **Locally**: The waste should be locally available.
- **Availability**: How much material is available within which time span? Is the supply of material constant, or very fluctuant?
- **Export**: Is the material currently being exported out of Europe?
- **Landfilling or incineration:** The material is considered waste when it is being landfilled or incinerated.
- **Process-ability**: How much processing is roughly needed? And how hand-able is the material? What does the composition of the material roughly consist of? Is the material toxic? Is there already a collection system for the material?

A material consideration decision tree is shown in figure 4.1.

Materials

Materials considered for further research were suggested by Renewi and found in literature research. Researched materials are grinding sludge, laser steel dust, steel shots and aluminium polymer foils. A brief description is given below.

Grinding sludge

Grinding sludge is produced during grinding and other metal forming processes. Grinding sludge is not purely metallic, but also consists of water, metal chips, abrasives (often ceramic) and lubricants (oil).

Laser steel dust

Laser steel dust is a fine particle material formed when laser cutting steel. The metal evaporates under the heat of the laser. The steel forms oxides with oxygen, cools down and solidifies again.

Steel shots

Steel shots are pellets used as an abrasive material in multiple industrial processes. They are used in surface preparation, cleaning and shot peeing. Often the steel shots residue consists of steel shots and other, often metallic particles, originating from the processed material.

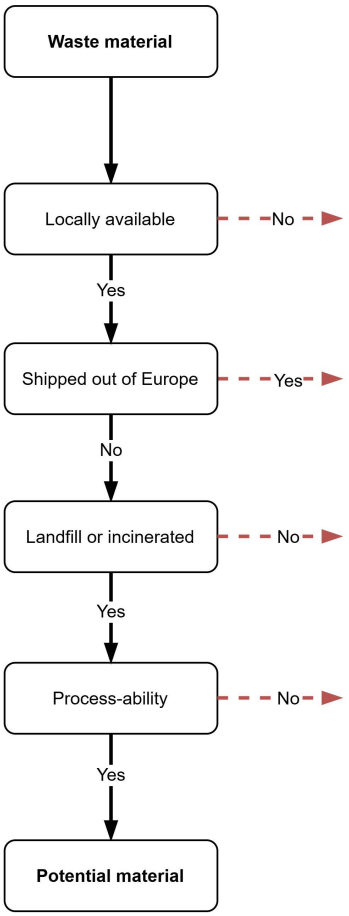
Aluminium polymer foils

Aluminium polymer foils are a composite of aluminium and polymers. They are often used as packaging or vapour barrier material. Production of these materials commonly takes place in China.

Material choice

After comparing different waste materials, the preferred material for this research are aluminium polymer foils. Due to its large availability the material waste stream is large enough for potential repurposing. Also, the aluminium in the composite is a material defined by the EU as critical (European Commission and Directorate-General for Internal Market Industry Entrepreneurship and SMEs et al., 2023).

Figure 4.1: *Material consideration decision tree.*



Aluminium in architecture

Aluminium is used in a wide variety of architectural applications. Aluminium is a lightweight material with high flexural strength. Therefore, it is often used for structural purposes. However, the main structure of a building is generally made up of different materials such as wood, steel or concrete. Aluminium is typically used in secondary structural systems, such as mounting systems for facade cladding, metal stud profiles for interior walls or tracks for mounting ceiling plates. For example, as mounting brackets or fixtures for bigger elements.

Due to its excellent weather resistance, it is also frequently used for outdoor applications. This can be for an aluminium substructure or for cladding. For surface applications, aluminium is of particular interest for its variety of different surface finishing techniques, such as anodising, coating or painting.

In addition to its use for cladding and framing, aluminium is also applied in large scale as curtain wall systems, roofing panels, sunshades, and louvers.

Framing

Aluminium is often used for window and door frames. This is because the extrusion process of aluminium offers an easy way of producing complicated profile sections for fixing rubber seals and other components. High performance glazing systems are often designed with thermal breaks to improve their insulative capability by reducing the thermal bridges. Aluminium is very low maintenance and keep their shape and appearance over time, even under harsh conditions.

5

Aluminium polymer composites

Aluminium polymer composite foils

Aluminium polymer composites (APC) have advantages compared to other single material foils. Their mechanical, physical and chemical properties are superior in comparison to single material foils. Examples are: flexible, UV resistant and airtight. Separations of APCs from municipal solid waste brings difficulties and there are, according to Al Mahmood et al., 2020; Cervantes-Reyes et al., 2015 no established methods in reports other than manual separation. Consequently, the majority of APCs and up in landfill or are being incinerated, although when separated, both metallic and polymeric fractions would be recyclable.

Composition

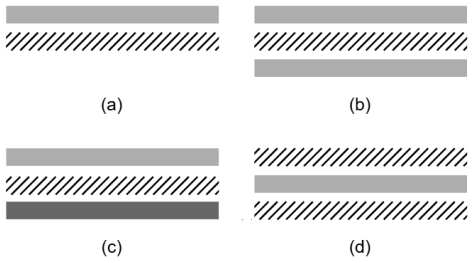
APCs can be built up in different compositions. When a composite consists of only two layers with two materials it is called a duplex composite. The industry also knows triplex composites. These composites consist of three layers of material. Multi-layers laminates are also very common (Cervantes-Reyes et al., 2015). Different layer configurations are show in figure 5.1. APCs can differ from each other in many parameters like type of material used, number of layers, layer thickness and production process. All of these parameters can have influence on the amount of effort it costs to recycle the material.

Material compositions are defined based on the desired physical properties of the material. Foils often consist of aluminium, multiple polymers or paper.

Products

APCs are used in countless applications. For example: beverage cans, tubes, foils, trays, blister packs, laminated pouches, aerosol containers, food packaging, cosmetics, medicine packaging, insulative flooring underlayment, vapour barriers, composite panels, coffee capsules, etc. (Al Mahmood et al., 2020). Depending on the applications, different compositions and material thicknesses are used. An overview of the most commonly used polymers and their function is given in table 5.1.

Figure 5.1: *APC compositions*



Note: The figure shows an overview of the four most common APC compositions. The striped layer representing the aluminium and the grey layer representing the polymer. Duplex composite (a) and triplex composite (b), (c), (d).

Polymer properties

A variety of polymers and aluminium types are utilised in composites; each designed for a particular purpose. A selection of frequently used polymers is outlined in table 5.2. The table also provides a comprehensive overview of the material properties and common applications.

Most packaging applications make use of thermoplastic polymers, because of their flexible character.

Aluminium foil

Primary aluminium (Al) is produced using the Bayer process and the Hall-Héroult electrolytic process. Aluminium oxide (Al_2O_3), retrieved from mining bauxite (aluminium ore) is processed using the Bayer process and is pure enough afterwards for aluminium electrolysis. The Bayer process is nearly unchanged and almost all the worlds alumina supply

Table 5.1: *Typical examples of aluminium polymer composite foils*

Product	Type of laminate
Coffee packaging	12µm Metallised nylon - 50µm Polyethylene
Savoury snacks	18µm Polypropylene - Adhesive - 18µm Metallised polypropylene
Spices	12µm Metallised polyethylene terephthalate - 38µm Polyethylene
Bag-in-box wine	50µm Ionomer - 12µm Metallised polyethylene terephthalate - 75µm EVA
Biscuits	Polypropylene - 18µm Metallised polypropylene
Medical products	Paper - Adhesive - 18µm Metallised polypropylene - Ionomer
Cold meats	Metallised polyethylene terephthalate - Polyethylene

Note: Common packaging products using APCs and their laminate type (Kerry, 2012).

Table 5.2: *APC composition material properties*

Material	Type	Melting point (°C)	Combustion CO_2 (kg/kg)	ρ(kg/m^3)
Aluminium	n.a.	580 - 650	n.a.	2690 - 2730
Polymer	Polyethylene (PE)	125 -132	3,06 - 3,22	939 - 960
	Polyvinyl chloride (PVC)	100 - 260	1,08 - 1,44	1290 - 1460
	Polyethylene terephthalate (PET)	250 -260	2,24 - 2,35	1290 - 1390
	Polypropylene (PP)	140 - 150	3,06 - 3,22	895 - 909
	Polyamide (PA6)	227 - 238	2,47 - 2,6	1001 - 1003
	Ethylene vinyl alcohol (EVOH)	142 - 191	2,73 - 2,87	1120 - 1200
	Polyvinylidene chloride (PVDC)	163 - 181	0,89 - 0,93	1650 - 1720
	Low-density polyethylene (LDPE)	110 - 121	x	x
	Ethylene vinyl acetate (EVA)	145 - 240	x	945 - 955
	Ionomer	82 - 94	2,68 - 2,82	934 - 950

Note: Commonly used polymers in aluminium polymer composite foils. Values containing (x)had no information in Ansys. Material properties retrieved from ANSYS, Inc., 2023 and Morris, 2017.

(Tabereaux & Peterson, 2014).

After pure aluminium is obtained it can be alloyed with for example coper (Cu), magnesium (Mg), manganese (Mn), zinc (Zn) or silicon (Si). The alloying system of aluminium is shown in figure 5.2. These alloying elements change the physical character of the aluminium and can be used for specific applications. A numeric system is used to name the type of alloying material used in the aluminium. These families are also shown in figure 5.2. It makes economically the most sense to return the alloy to the same alloy or at least the same family when the material is recycled (Tabereaux & Peterson, 2014).

Production of aluminium foil

Production of aluminium foil can be done by two processes: Rolling aluminium slabs, ingots, or plates into thin aluminium stock using rolling mills (fig. 5.3) or continuous casting, immediately after the aluminium has left the furnace (fig. 5.4).

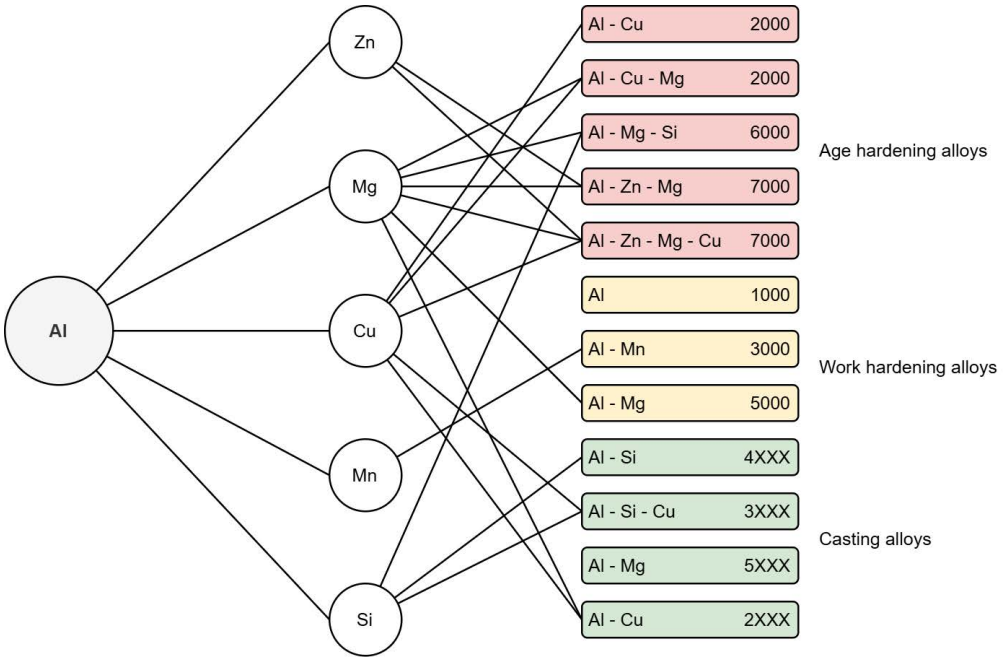
The rolling process can be considered as a form of extrusion. The rolling length of the aluminium foil changes during the rolling process. Material gets pushed 'away'; this adds length. The width of the foil is constant during the whole process.

After rolling the foil is annealed to overcome hardening. The foil is polished to ensure a shiny and flat surface. Foils under gauge 25 µm are usually worked through the rolls in two webs to prevent tearing.

Coatings can be added to increase heat-resistance, strength, corrosion protection, UV resistance or scratching protection (Kerry, 2012).

Aluminium foils are commonly less than 150 µm in thickness. Heavier foils are considered above gauges >17 µm and

Figure 5.2: *Aluminium alloying system in principle.*



Note: Aluminium alloying system and their alloying elements. Specific aluminium series are noted on the right side of the figure. (Tabereaux & Peterson, 2014).

provide a 100% barrier to gases and liquids (Kerry, 2012).

Lamination

Lamination involves combing different sheets of material into one single sheet. Adhesives are selected based on their suitability for the selected materials. Different types of adhesives commonly used to laminate aluminium foil:

- wet bonding
- dry bonding
- extrusion bonding
- hot-melt bonding

When wet bonding, multiple layers are combined before the drying of the adhesive is done. A solvent- or water-based adhesive is applied to the aluminium foil. The adhesive is dried in a drying oven. For the adhesive to ad hear properly the material needs to be porous.

Dry bonding is used for non-porous materials and uses an agent. The adhesive is applied to the foil and dried. After drying the foil is fed through a heated combiner roller and adhered another layer material.

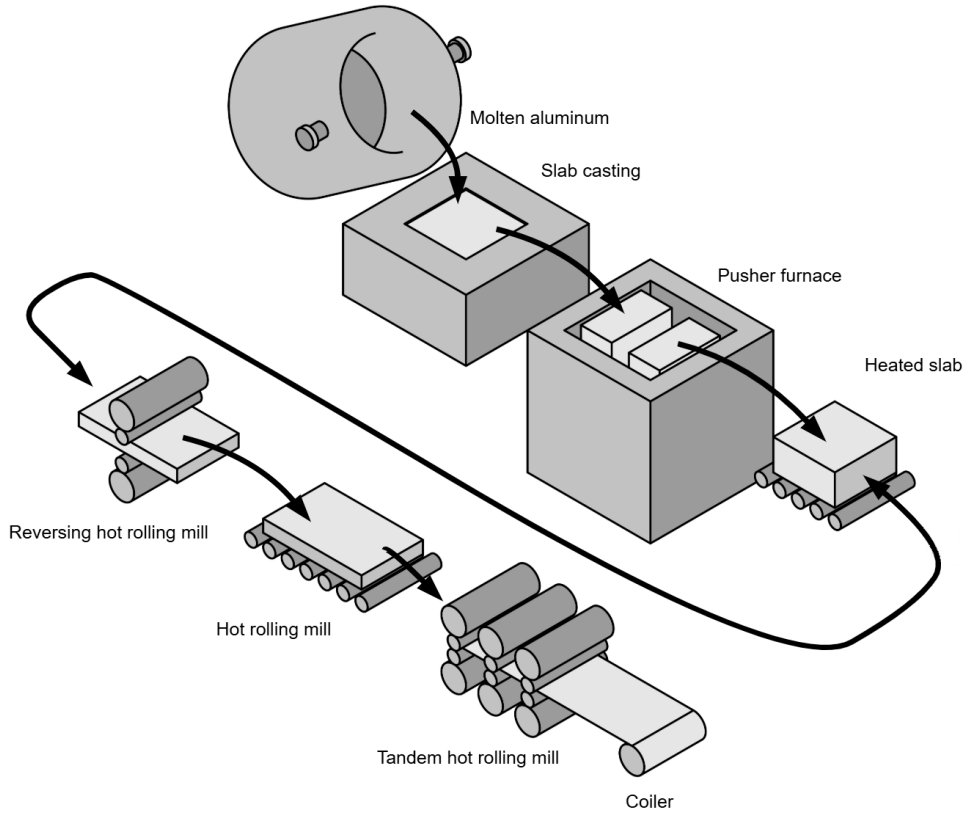
When extrusion bonding a molten film of polymer is deposited on the aluminium foil. The foil passes through a cooling roller and the adhesion is complete. This process is also used when coating an aluminium foil.

Hot-melt bonding is used for high-speed lamination. Just like extrusion bonding, there is no need for drying time. Compared to extrusion bonding hot-melt bonding is performed at a lower temperature.

Vacuum metallising

Vacuum metallising is a process that involves applying a thin metal layer onto a substrate such as paper or plastic film. This is performed in a vacuum

Figure 5.3: *Rolling-mill to produce aluminium foil.*



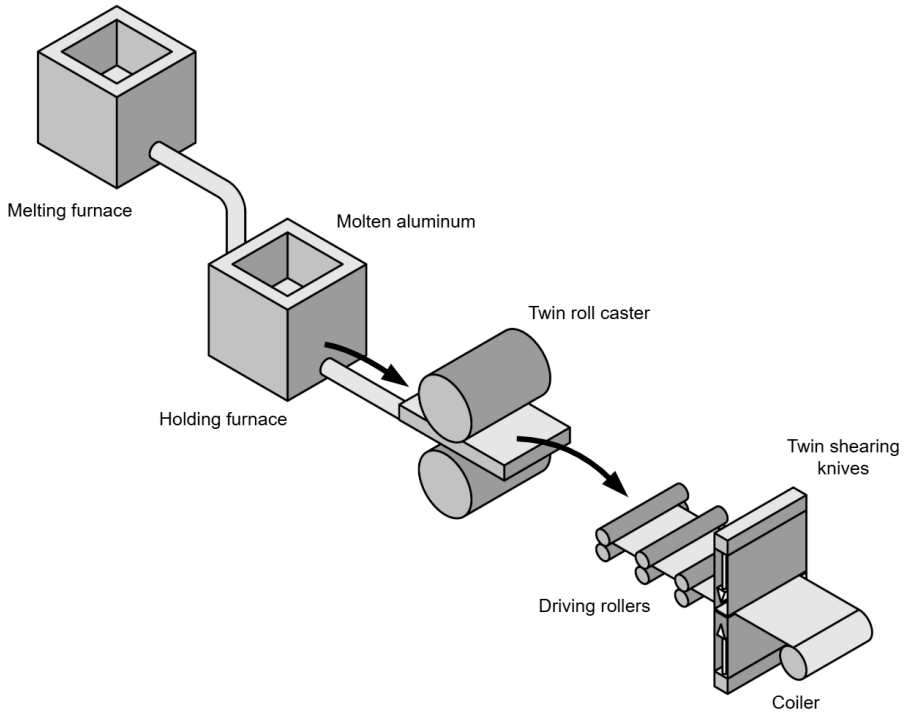
Note:

environment. The layer thickness of the metal, aluminium in most cases, can reach small gauge than in when using rolling processes.

Due to the high temperatures required, the metal layer, often aluminium, must be shielded by a heat-resistant coating like polyester. The most common method used for metallising is batch processing. In this setup, the substrate is transported through the chamber by a series of rollers, while the chamber is in a vacuum. Aluminium wire is placed in containers, or 'boats', which are heated to vapourise the metal (the vacuum lowers the vapourisation temperature of aluminium and prevents oxidation). The vapour then rises and condenses on the underside of the substrate as it moves over a cooled roller. The thickness of the metal layer is controlled by adjusting factors such as the speed of the substrate, the rate of wire feed, and the temperature of the boats (fig. 5.5).

For metallised papers, it is important to use high-quality virgin paper with a clay coating to ensure a smooth surface and strong reflectivity in the finished product. While various plastic films can also be metallised, materials like PP, PET, Nylon are the most common types used for packaging films. Unlike paper, plastic films

Figure 5.4: *Continuous casting to produce aluminium foil.*



Note:

do not require sealing before they can be metallised (Kerry, 2012).

Recycling

The different compositions of different APCs difficult recycling processes. The material mass ratios between aluminium and polymer influences recycling approaches. Also, depending on the type of polymer used in the foil, recycling processes can differ.

When recycling APCs, the layer thickness of materials in the composition is of importance. Defining this thickness can be done by analysing a cross section of the foil with a microscope. The polymer type in samples can be identified using a Fourier transform infrared spectrometer (FTIR) (Al Mahmood et al., 2020).

Separation techniques

The components of APCs are strongly adhered and hard to separate by mechanical processes (Al Mahmood et al., 2020). The methods described below are proven functional for separation of aluminium from composite foils.

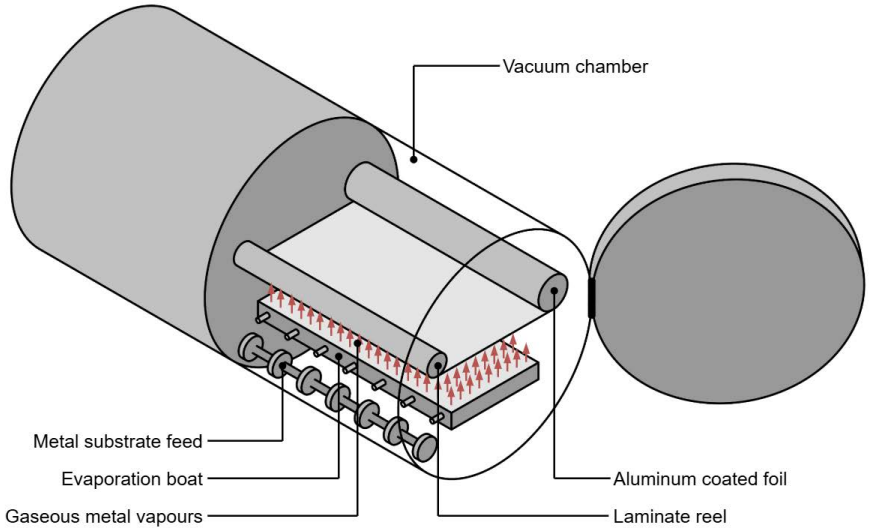
Pyrometallurgy

Traditional smelting methods for APC materials face significant challenges, including high material loss and the absence of effective control mechanisms during the process.

Dissolving

Chemical processes such as hydrolysis, alcoholysis, and glycolysis employ basic, alcoholic, and acidic solvents to promote the depolymerisation of aluminium

Figure 5.5: *Vacuum metallising foil production*



Note:

materials. Though these methods result in recycled materials of reasonable quality, they are known to be excessively time-consuming and costly.

As discussed in section 3 dissolving also known as hydrometallurgy can be used to dissolve materials. This can be done in aqueous solutions or organic solutions. Examples of aqueous solutions dissolving aluminium is formic acid or acetic acid. Dissolving polymers can be performed by for example xylene, hexane, acetone or ethanol (Cervantes-Reyes et al., 2015). However effective, dissolving material is costly and has environmentally a high impact.

Thermal disengagement technology (TDT)

A thermal disengagement experiment was performed by Al Mahmood et al., 2020. Sample material of APCs was brought in as well arid as inert environment to a temperature above the melting point of the polymer, but below temperature of the aluminium. The polymer will decompose, only the aluminium remains. This method is useful for high percentage aluminium composites. However, for low percentage aluminium composites this method can be problematic due to lack in structural of the aluminium layer of the composite.

Al Mahmood et al., 2020, Al Mahmood et al., 2019 and Riedewald et al., 2022 all did similar promising studies on the application of TDT on aluminium composites.

Conclusion

Aluminium polymer composites have advantages in comparison to single layer foils. However, this lamination creates challenges for recycling of this material. This results in most APCs being landfilled or incinerated.

Recycling APCs is complex due to the strongly adhered layers. Different techniques are being researched to separate the layers, but no mayor

breakthrough seems to show. This thesis will explore different solutions to recycle these materials

CaixaForum Sevilla / Vázquez Consuegra. Photograph by Duccio Malagamba (Rojas, 2025)

6

Aluminium foaming

.

Chapter 3 describes different techniques of forming metals. One of the described techniques is powder metallurgy. Using this technique combinations of elements can be made that would not be possible using other metal forming techniques. The presence of polymer and aluminium in APC's raised the question whether these materials could be combined in some sort using a powder metallurgical approach. This section describes foaming techniques using a powder metallurgical approach to research a potential reprocessing technique for these materials.

Metallic foams

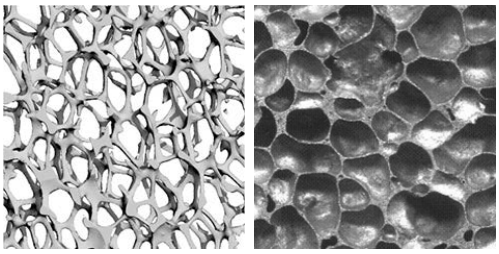
Metallic foam can be formed using a variety of techniques. Depending on the production technique, two main cell morphologies can be derived. The cell morphology can be classified in two types: open cell (sponge) or closed cell (foam). Characteristics of both are described in table 6.1. Figure 6.1 illustrates the open cell and closed cell morphology of the foam. Cell structures are depended on the production method.

Table 6.1: *Classification of open cell and closed cell metallic foams*

Open cell	Closed cell
Complex cells, interconnected.	Cell faces and edges are clear, not interconnected
Low density	Higher density
Low compressive strength	High compressive strength
High porosity, lightweight	High energy and crash absorption
Used in filters, heat exchangers	Used in impact absorption, dampening

Note: Cell morphology classification (Hassan & Alnaser, 2024).

Figure 6.1: *Cell morphology*



(a) *Open cell* **(b)** *Closed cell*

Note: Classification of different foam morphologies (Hassan & Alnaser, 2024).

Production and processing techniques

Metallic foams are produced with advanced manufacturing techniques. Depending on the processing parameters different cell characteristics will occur. Depending on the required pore structure the manufacturing processes can differ. For open-cell structures, solid or powder metallurgical processes are preferred. Liquid or melting methods are used for closed cell structures are required.

The production process can be classified in four main categories: liquid state (melt), solid state (powder metallurgy), metal vapour, and metal ion solution (Hassan & Alnaser, 2024).

For this research only liquid state and solid state are considered.

Liquid state

When liquid state foaming, the metal is heated above its melting point. *Direct foaming* methods involve adding gas bubbles into the molten metal. The injected gas can range be CO_2, O_2, inert gases, or steam. An alternative for adding gas is introducing a foaming agent. The foaming agent is mixed into the metal before heating. While heating the foaming agent will release gas and makes the aluminium expend, forming bubbles. *Indirect foaming* methods make use of a space holder material reserving space for the pore structure.

Solid state

In the solid state process a metallic powder is used. The metal maintains solid throughout the whole procedure. Using different solid-state operations, metallic foam with usually an open cell morphology is formed. The shape and size of the metallic powder is highly essential for the eventual outcome of the foam.

Similar to the liquid state foaming using a foaming agent a foaming agent can be used in a solid-state approach. By mixing the agent in the metallic powder and compressing the mix into a green part will entrap the agent. By heating the green part, the agent will undergo decomposition, forming gas that will create bubbles in the foam.

Proposed techniques

Based on available laboratorial equipment, prior knowledge and overall feasibility the following techniques are studied in for the experimental phase.

Gas entrapment technique

A mixture of aluminium and a foaming agent is made in a specific ratio. Dependent on the foaming agent different weight percentage will have different morphological outcomes on the foamed aluminium. This mixture is pressurised and heated up until the melting point of aluminium. The solid foaming agent particles will transition to gas when heated. This will lead to expansion of the cell and will leave a cavity in the aluminium. When the mixture ratio is high enough, separated agent particles will interconnect to create an interconnected open-cell morphology. Gas is entrapped in between aluminium particles. This method is schematically shown in figure 6.2.

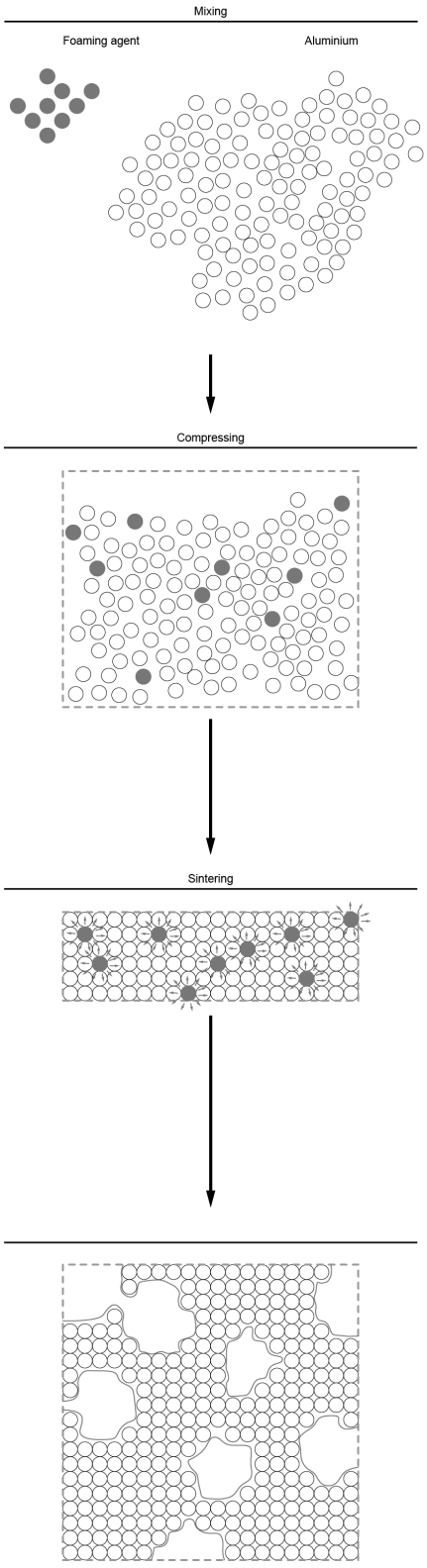
Space holder technique

Like with gas entrapment technique particles are mixed in the aluminium particles. On the contrary to the gas entrapment these particles will not transition to gas when heated but will keep their original form. The space holders are therefore, generally speaking, larger than when using gas entrapment technique. Particles are put in-between the aluminium particles. The aluminium melts around the space holder material. After cooling the aluminium, the space holder is removed. This can be done by dissolving the space holder, burning the space holder, or with other methods. This method is schematically shown in figure 6.3.

Aluminium composite foaming

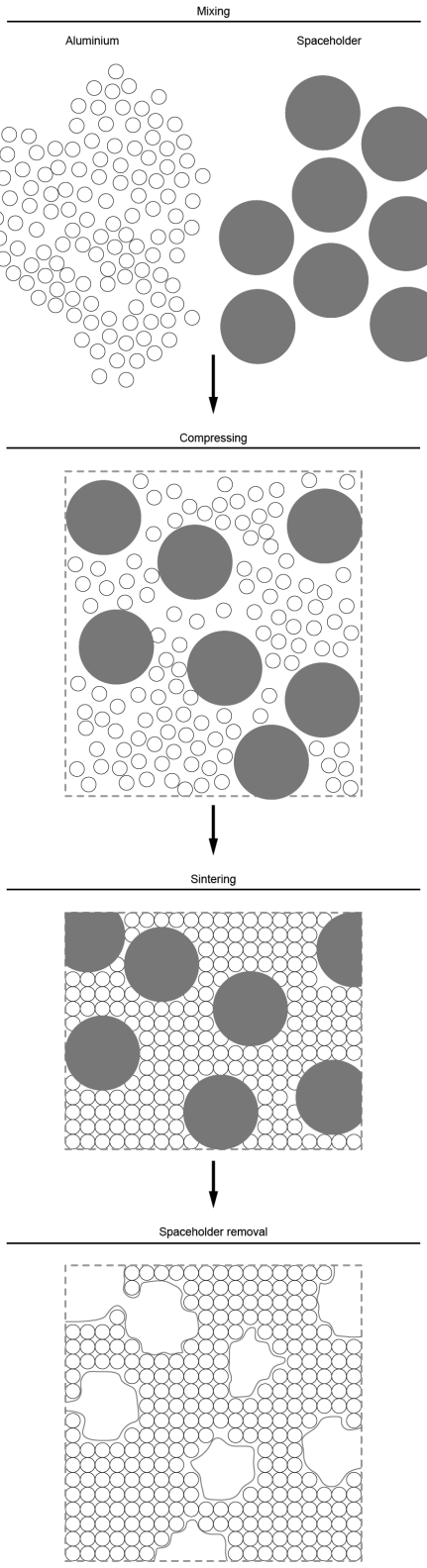
The aluminium composite foil described in the previous sections is researched using the techniques described above. Hypothetically the polymer can act as a space holder, or a foaming agent. Possibly it will function as both. The experimental phase of this research will focus on researching the foaming capabilities of the polymer on the aluminium present in the composite foil.

Figure 6.2: *Gas entrapment foaming*



Note: Simplified overview of metallic foaming using space gas entrapment technique.

Figure 6.3: *Space holder foaming*



Note: Simplified overview of metallic foaming using space holder technique.

7

Experiments

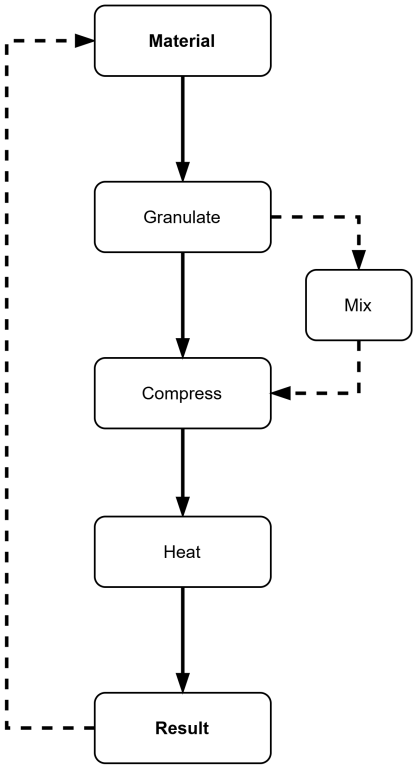
Framework & approach

Based on the production and recycling methods described in chapters 3 and 5 the assumption is made that there is potential in using a powder metallurgical approach in search of reprocessing un-recycled metal waste. Therefore, a series of experiments will follow; researching and designing a workflow to develop a material for architectural applications.

Workflow

As an introduction to the experiments a concept workflow is proposed. To guide the experiment documentation described in the following sections, figure 7.1 shows a schematic overview of this workflow. This workflow is closely related to power metallurgy techniques.

Figure 7.1: *Experimentation framework*



Sample material is retrieved from a variety of sources. If applicable, the material is cleaned with water and detergent to reduce further contamination and effect on experiment results. The sample material is granulated into different sizes to test the effect of granule size on the overall stability of the material. The material is compressed into a desired shape and heated in an oven. The sample is removed from the oven and will the results be evaluated. Depending on the outcome of the experiment, the parameters for each step are changed and the framework is repeated.

7.1

Material

Selected sample material

For this part of the experimentation a wide range of materials with different ratios of aluminium to polymer is selected for experimentation. The range will give a rough idea of the influence of mixing rates between the two parts of the mixture. For the polymer the focus is put on composite foils using polyethylene (PE). Polyethylene is a common polymer used in the packaging industry.

The selected materials are: crisp packets (S1), flooring underlayment (S2), coffee capsules (S3), and a variety of foils used as sealable lids (S5, S6 and S7). To gain a better understanding of the selected materials their layer thicknesses are estimated by measuring their cross section using a microscope. After estimating the layer thickness the ratio between aluminium and polyethylene is calculated. The material properties are noted in table 7.1.

A visual representation of the numbers in table 7.1 are shown in figure 7.2 and figure 7.3.

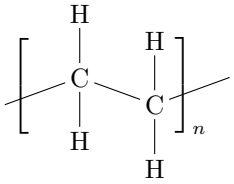
Validation of the sample characteristics was conducted using a microscope (Keyence VHX-7000 microscope) and a FTIR machine (Thermo Fisher Nicolet Nexus Fourier Transform Infrared Spectro-photometer). The results are shown in figure 7.5.

Materials considerations

Polyethylene

Polyethylene is a thermoplastic polymer made from the monomer ethylene (C_2H_4) and primarily produced by steam cracking hydrocarbons.

The molecular structure of polyethylene is:



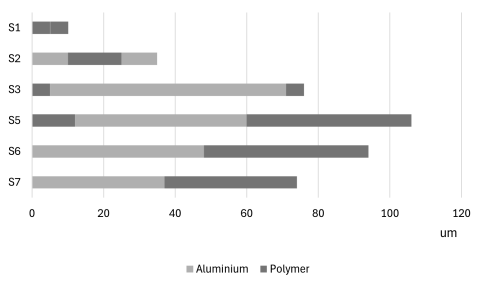
where n represents the degree of polymerization.

It is not uncommon to find added filler materials in polyethylene. $CaCO_3$, Mg^{2+} SiO, are often used as filler elements in the plastic to increase yield strength and stiffness (Bartczak et al., 1998).

Pyrolysis

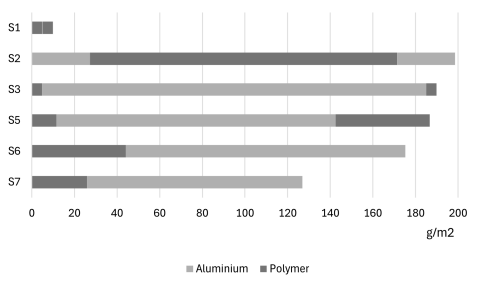
The pyrolysis of polyethylene produces various products in the form of gases, liquids and waxes. On average the liquid production results in octane (C_8H_{18}). Wax production results in paraffin with different with carbon chains ranging

Figure 7.2: *Bar chart of layer volume in sample material*



Note: Bar chart showing layer volume of different sample material, visualising information of table 7.1.

Figure 7.3: *Bar chart of layer mass in sample material*

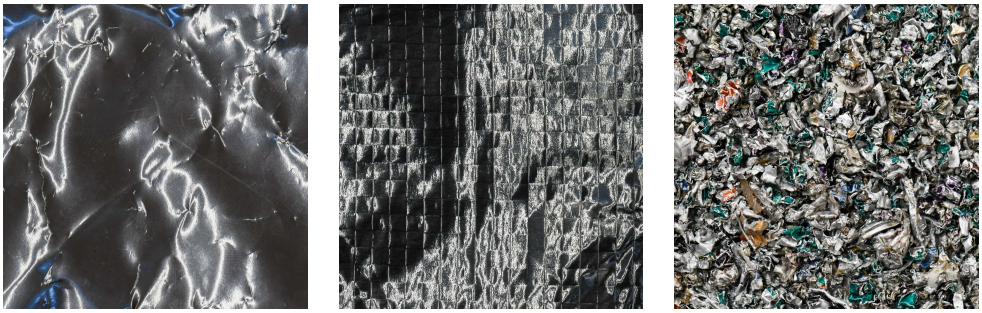


Note: Bar chart showing layer mass of different sample material, visualising information of table 7.1.

Table 7.1: *Material properties sample material*

Sample ID	Layer material	Layer thickness	wt%	mass ratio (Al-PE)	vol%	volume ratio (Al-PE)
S1	PP	5	48,6	2,8 - 97,2	49,5	1,0 - 99,0
	Al	0,1	2,8		1,0	
	PP	5	48,6		49,5	
S2	Al	10	13,7	27,5 - 72,5	5,9	11,8 - 88,2
	PE	150	72,5		88,2	
	Al	10	13,7		5,9	
S3	PE	5	2,5	94,5 - 5,5	6,6	86,8 - 13,2
	Al	66	94,9		86,8	
	PE	5	2,5		6,6	
S5	PET	12	6,2		11,3	
	Al	48	70,2	70,2 - 29,8	45,3	45,3 - 54,7
	PE	46	23,7		17,9	
S6	Al	48	74,8	74,8 - 25,2	57,8	51,1 - 48,9
	PE	46	25,2		48,9	
S7	Al	37	79,6	79,6 - 20,4	57,8	57,8 - 42,2
	PE	27	20,4		42,2	

Figure 7.4: *Sample materials*



(a) S1 **(b)** S2 **(c)** S3

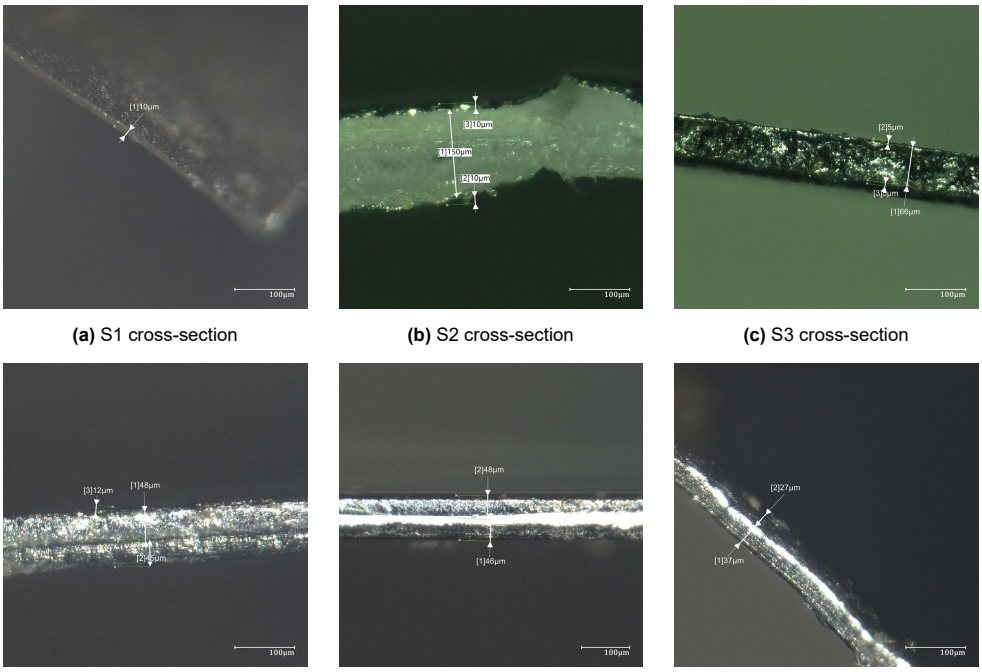
(d) S5 **(e)** S6 **(f)** S7

Note: Sample APC materials (7.4a, 7.4b, 7.4c, 7.4d, 7.4e, 7.4f).

from C_{20} to C_{30}. Pyrolysis carried out at lower temperatures (~400°c) results in a considerably higher amount of wax production. Higher temperatures (~>500°c) will result in higher amounts of octane production (Onwudili et al., 2009).

These products can be collected and used in other industries, but this would require the ample to be heated in an oxygen-limited environment.

Figure 7.5: *Cross-connection of sample materials*



(a) S1 cross-section **(b)** S2 cross-section **(c)** S3 cross-section

(d) S5 cross-section **(e)** S6 cross-section **(f)** S7 cross-section

Note: Cross-sectional view of the sample APC materials (7.5a, 7.5b, 7.5c, 7.5d, 7.5e, 7.5f) showing polymer lamination. Made with Keyence VHX-7000 microscope, at 500x magnification.

This can be done by using a pyrolysis oven as shown in figure 7.7. The material is heated in an oxygen-limited environment which can be created in a number of ways.

After the polymer turns is converted in to a gaseous state, the gases are condensed and collected (in liquid state) for further use.

However, some of the carbon atoms in the polymer will partially from a carbon deposit during the pyrolysis. This carbon deposit is much smaller when heated in an oxygen rich environment. In this situation the carbon will react with the oxygen and will form carbon dioxide (CO_2). This is not possible in the absence of oxygen.

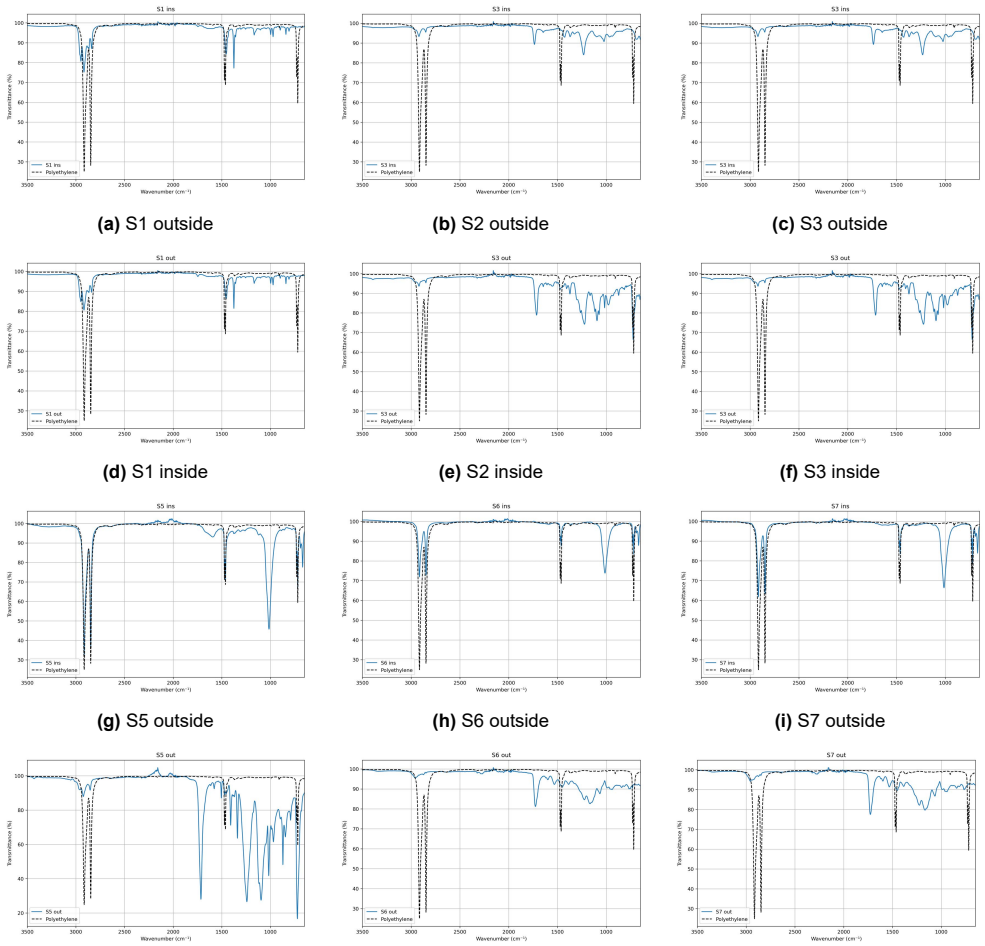
Aluminium

Some background information on aluminium has already been described in the previous sections. Therefore, this section will only focus on considerations when introducing aluminium to elevated temperatures.

Oxidation

When exposed to an oxygen environment aluminium naturally forms an oxide layer on its surface. This oxide layer protects the aluminium from further oxidation and is often considered as desirable. However, at elevated temperatures the mass of the aluminium oxide (alumina) begins to increase rapidly. This can be divided into four stages. This is shown in figure 7.8. The figure shows that at temperatures above 900°c aluminium oxide formation will increase rapidly. To prevent this, it

Figure 7.6: *Inside and outside fourier analysis of sample materials*



(a) S1 outside **(b)** S2 outside **(c)** S3 outside

(d) S1 inside **(e)** S2 inside **(f)** S3 inside

(g) S5 outside **(h)** S6 outside **(i)** S7 outside

(j) S5 inside **(k)** S6 inside **(l)** S7 inside

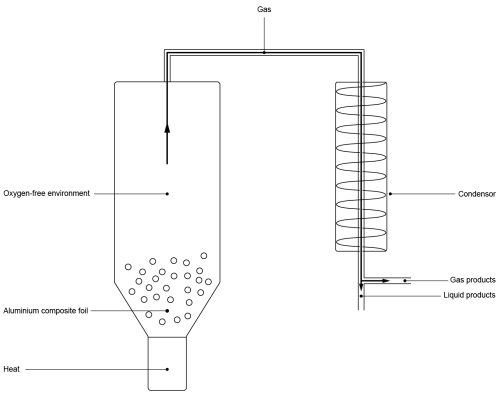
Note: FTIR of the polymers laminate inside of the sample (S1 (7.6a), S2 (7.6b), S3 (7.6c), S5 (7.6g, S6 (7.6h, S7 (7.6i) and FTIR of the polymers laminated outside of the packaging (7.6d, 7.6e, 7.6f, 7.6j, 7.6k, 7.6l).

is important to avoid temperatures above this level and to reduce the exposure time to temperatures close to this level (Coker, 2013).

Carbonation

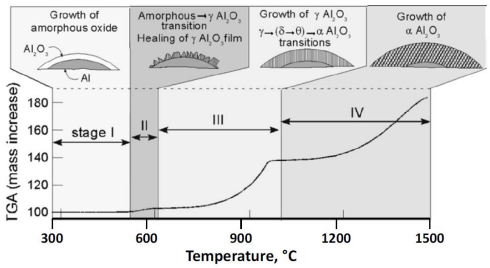
At high temperatures aluminium has the tendency to form aluminium carbide (Al_4C_3) when in contact with carbon atoms. At higher temperatures the rate of growth of aluminium carbide increases due to the increased reactivity between carbon and aluminium (Mendoza-Duarte et al., 2024). Aluminium carbide is stable up until 1400°C. Its melting point lays at 2200°C.

Figure 7.7: *Pyrolysis oven*



Note: Schematic overview of the main elements of a pyrolysis oven. Based on Somsuk et al., 2009.

Figure 7.8: *Oxide formation on aluminium surfaces at elevated temperature*



Note: Aluminium oxide mass increase for different temperatures. Retrieved from Coker, 2013.

7.2
Size reduction & pallet pressing

Size reduction

The size of the aluminium foil will have to be reduced to perform further experimentation and testing. Multiple, unconventional, shredding techniques are researched in this section in search for desired results.

As a starting point the following particle sizes were aimed for when searching for effective size reduction methods.

- Powder <2mm
- Flakes 2-20mm
- Strings >50mm

These granule sizes are larger than those typically used in conventional powder metallurgy. However, this choice was made for reasons of feasibility. Moreover, this form of powder metallurgy is far from conventional; therefore, so it is assumed that the particle size may also deviate from conventional norms.

Initially, an industrial granulating machine (Retsch SM 2000, 750 rpm) was tried to granulate the foil (figure 7.9). The machine uses a set of rotating blades to catch the material and break it into smaller pieces. A sieve is placed on the bottom of the machine, where the shredded particles will leave the machine. The sieve will sort the shredded pieces into to desired size. Particles that are still larger than the desired size can be run through the machine again for further size reduction.

However, due to its shape and material properties, aluminium composite foils are proven to be difficult to granulate the material using this shredder. The material has a high tensile strength and is very flexible. This hinders the crushing and shredding of the foil. The form of the foil (thin) makes it difficult to catch in the shredder. The blades in the machine were too coarse for the foils, resulting in clogging and not to a shredded result. When the foil did get caught in the machine, the result was large shreds rather than the desired small flake sizes.

Figure 7.9: *Retsch shredder*

Note: Retsch SM 2000, 750 rpm, commonly used to shred brittle materials like concrete or plastics.

Alternative shredding techniques

After trying the Retsch SM 2000, 750 rpm shredder a Microtools MPS 110 paper shredder was tried to reduce the size of the material. For the different sample materials this gave various results. In general, a higher percentage of aluminium in the foil would give better results. For foils with very low aluminium content (S1 and S2), the machine did not shred the material. In these cases, the material was

cut with scissors.

After this first step of size reduction a kitchen blender (Kenwood Multipro blender) was used to try and reduce the size of the foils (figure 7.11). Adding water helped creating resistance on the material so the blades of the shredder would have more effect. This resulted in various shred sizes with some consistency. The material was removed from the blender and dried in an oven at 90°C after all the moisture had evaporated from the material.

To reach even smaller granulation sizes a coffee grinder (Gaggia MDF coffeegrinder) was tried to granulate (figure 7.12). This gave the best (smallest) result. This method was particularly effective for foils with a higher aluminium content.

After granulation the material was sieved using sieves in the desired granulation sizes. The material was stored in air tight plastic bags for further use.

The used workflow shows to be effective to reduce the size of the aluminium polymer composite foil. Although effective, this method is highly time intensive and not shown to be very consistent.

Mix ratio

An obstacle is the non-uniform granulation between the different materials in the composition. When the foil is granulated, the aluminium tends to break into smaller pieces than the polymer. This results in small aluminium particles and larger polymer particles. Especially sample material S2 poses this problem. When using a sieve to obtain consistent particle sizes this leaves an undefined mix ratio between the aluminium and polymer. This makes it difficult to ensure the consistency of tests later on. Although, this makes it difficult to define the mixing ratios, it is actually beneficial when trying to separate the aluminium from the polymer layer.

Figure 7.10: *Paper shredder*

Note: Microtools MPS 110 paper shredder, commonly used as office equipment.

Figure 7.11: *Kenwood blender*

Note: Kenwood multipro blender, commonly used as kitchen equipment.

Compressing

Pallets were pressed from all the sample materials. The initial pallets were pressed using only 2,5g of material. This small

Figure 7.12: *Gaggia coffee grinder*

Note: Modified Gaggia MDF coffee grinder, variable granulation sizes.

amount of material was preferred because most of the materials were very time consuming to granulate to the desired size. The material was placed in a die (ø ~32 mm) and compressed at 230 MPa (25.000 kg equivalent) using a hydraulic press (Beckman 25 ton manual hydraulic press). The samples were compressed at room temperature (20°C) and were held at the target pressure for 60 seconds. Afterwards the sample was stored in an airtight plastic bag. The different pressed pallets. produced using the smallest (<2mm) granulation size, are noted in table 7.2 and shown in figure 7.13.

Results powder

The samples with lower aluminium content (S1, S2) showed deformation after pressing. This deformation was caused by the polymer shreds returning to their original shape before pressing. To reduce the deformation after pressing, a second set of samples was pressed at 110°C, also shown in table 7.2. These samples showed less deformation and retained its desired shape. The samples compressed at 20°C are shown in figure 7.13. The samples compressed at 110°C are shown in figure 7.14.

The same experiments were repeated for the other two grain sizes. The samples are listed in table 7.3(2-20mm) and 7.4(<20mm) and shown in figure 7.15 and figure 7.17.

All samples are firm enough to be picked up with care. However, they do not give the impression that they are firm enough to serve any architectural purpose. The samples are brittle and can be easily broken or pulled apart.

Results flakes

The samples with lower aluminium content (S1, S2) again showed deformation after pressing. In order to reduce the deformation after pressing, a second set of samples was pressed at 110°C, also shown in table 7.3. These samples showed less deformation from the polymer and retained its desired shape. The samples compressed at 20°C are shown in figure 7.15. The samples compressed at 110°C are shown in figure 7.16. Sample S4 was not compressed because the original shape of the material did not meet the requirements to obtain the desired granule size. Samples from S5, S6 and S7 were not compressed at 110°C because they did not show any deformation after compression at 20°C.

The samples are fluffy and can be easily pulled apart. The polymer showed deformation but no clear sign of binding at these temperatures.

Table 7.2: *Pressed pallets | Powder*

Sample	Grain size	Compaction (MPa)	Temperature (°C)
S1.P.CR*	Powder (<2mm)	230	20
S2.P.CR	Powder (<2mm)	230	20
S3.P.CR	Powder (<2mm)	230	20
S4.P.CR	Powder (<2mm)	230	20
S5.P.CR	Powder (<2mm)	230	20
S6.P.CR	Powder (<2mm)	230	20
S7.P.CR	Powder (<2mm)	230	20
S1.P.CH	Powder (<2mm)	230	110
S2.P.CH	Powder (<2mm)	230	110
S3.P.CH	Powder (<2mm)	230	110
S4.P.CH	Powder (<2mm)	230	110
S5.P.CH	Powder (<2mm)	230	110
S6.P.CH	Powder (<2mm)	230	110
S7.P.CH	Powder (<2mm)	230	110

Note: Sample names marked with * were excluded from testing because the sample failed to maintain its intended shape after pressing. Sample names marked with ** were excluded from testing because the sample material did not meet the granulation size.

Figure 7.13: *Compacted sample material | Powder | 20*

(a) S2.P.CR **(b)** S3.P.CR **(c)** S4.P.CR

(d) S5.P.CR **(e)** S6.P.CR **(f)** S7.P.CR

Note: Powder granulates of different sample materials compressed at 230 MPa at room temperature.

Results strings

The samples with lower aluminium content (S1, S2) again showed deformation after pressing. To reduce deformation after pressing, a second set of samples was pressed at 110°C, also shown in table 7.4. These samples showed less deformation from the polymer and the sample retained

Figure 7.14: *Compacted sample material | Powder | 110*

(a) S1.P.CH

(b) S2.P.CH

(c) S3.P.CH

(d) S4.P.CH

Note: Powder granulates of different sample materials compressed at 230 MPa at 110°C.

Table 7.3: *Pressed pallets | Flakes*

Sample	Grain size	Compaction (MPa)	Temperature (°C)
S1.F.CR*	Flakes (2-20mm)	230	20
S2.F.CR	Flakes (2-20mm)	230	20
S3.F.CR	Flakes (2-20mm)	230	20
S4.F.CR*	Flakes (2-20mm)	230	20
S5.F.CR	Flakes (2-20mm)	230	20
S6.F.CR	Flakes (2-20mm)	230	20
S7.F.CR	Flakes (2-20mm)	230	20
S1.F.CH	Flakes (2-20mm)	230	110
S2.F.CH	Flakes (2-20mm)	230	110
S3.F.CH	Flakes (2-20mm)	230	110
S4.F.CH*	Flakes (2-20mm)	230	110
S5.P.CH	Flakes (2-20mm)	230	110
S6.P.CH	Flakes (2-20mm)	230	110
S7.P.CH	Flakes (2-20mm)	230	110

Note: Sample names marked with * were excluded from testing because the sample failed to maintain its intended shape after pressing. Sample names marked with ** were excluded from testing because the sample material did not meet the granulation size.

their desired shape. The samples compressed at 20°C are shown in figure 7.17. The samples compressed at 110°C are shown in figure 7.18. Samples S3 and S4 were not compressed because the original form of the material did not meet the requirements to get the desired granule size. Samples S5, S6 and S7

Figure 7.15: *Compacted sample material | Flakes | 20*

(a) S1.F.CR* **(b)** S2.F.CR **(c)** S3.F.CR

(d) S5.F.CR **(e)** S6.F.CR **(f)** S7.F.CR

Note: Flake granulates of different sample materials compressed at 230 MPa at room temperature.

Figure 7.16: *Compacted sample material | Flakes | 110*

(a) S1.F.CH **(b)** S2.F.CH **(c)** S3.F.CH

Note: Flake granulates of different sample materials compressed at 230 MPa at 110°C.

were not compressed at 110°C, because they showed no deformation after pressing at room temperature. Therefore, it was not intended to deform the polymer by increasing the compression temperature.

Conclusion

The experiment shows that after compaction the samples remain in the desired shape. Samples with higher aluminium content tend to stay in the desired shape better than samples with lower aluminium content. A higher

Table 7.4: *Pressed pallets | Strings*

Sample	Grain size	Compaction (MPa)	Temperature (°C)
S1.S.CR	Strings (>50mm)	230	20
S2.S.CR	Strings (>50mm)	230	20
S3.S.CR**	Strings (>50mm)	230	20
S4.S.CR**	Strings (>50mm)	230	20
S5.P.CR	Strings (>50mm)	230	20
S6.P.CR	Strings (>50mm)	230	20
S7.P.CR	Strings (>50mm)	230	20
S1.S.CH	Strings (>50mm)	230	110
S2.S.CH	Strings (>50mm)	230	110
S3.S.CH**	Strings (>50mm)	230	110
S4.S.CH**	Strings (>50mm)	230	110
S5.P.CH	Strings (>50mm)	230	110
S6.P.CH	Strings (>50mm)	230	110
S7.P.CH	Strings (>50mm)	230	110

Note: Sample names marked with * were excluded from testing because the sample failed to maintain its intended shape after pressing. Sample names marked with ** were excluded from testing because the sample material did not meet the granulation size.

Figure 7.17: *Compacted sample material | Strings | 20*

(a) S1.S.CR **(b)** S2.S.CR

(c) S5.S.CR* **(d)** S6.S.CR* **(e)** S7.S.CR*

Note: String granulates of different sample materials compressed at 230 MPa at room temperature.

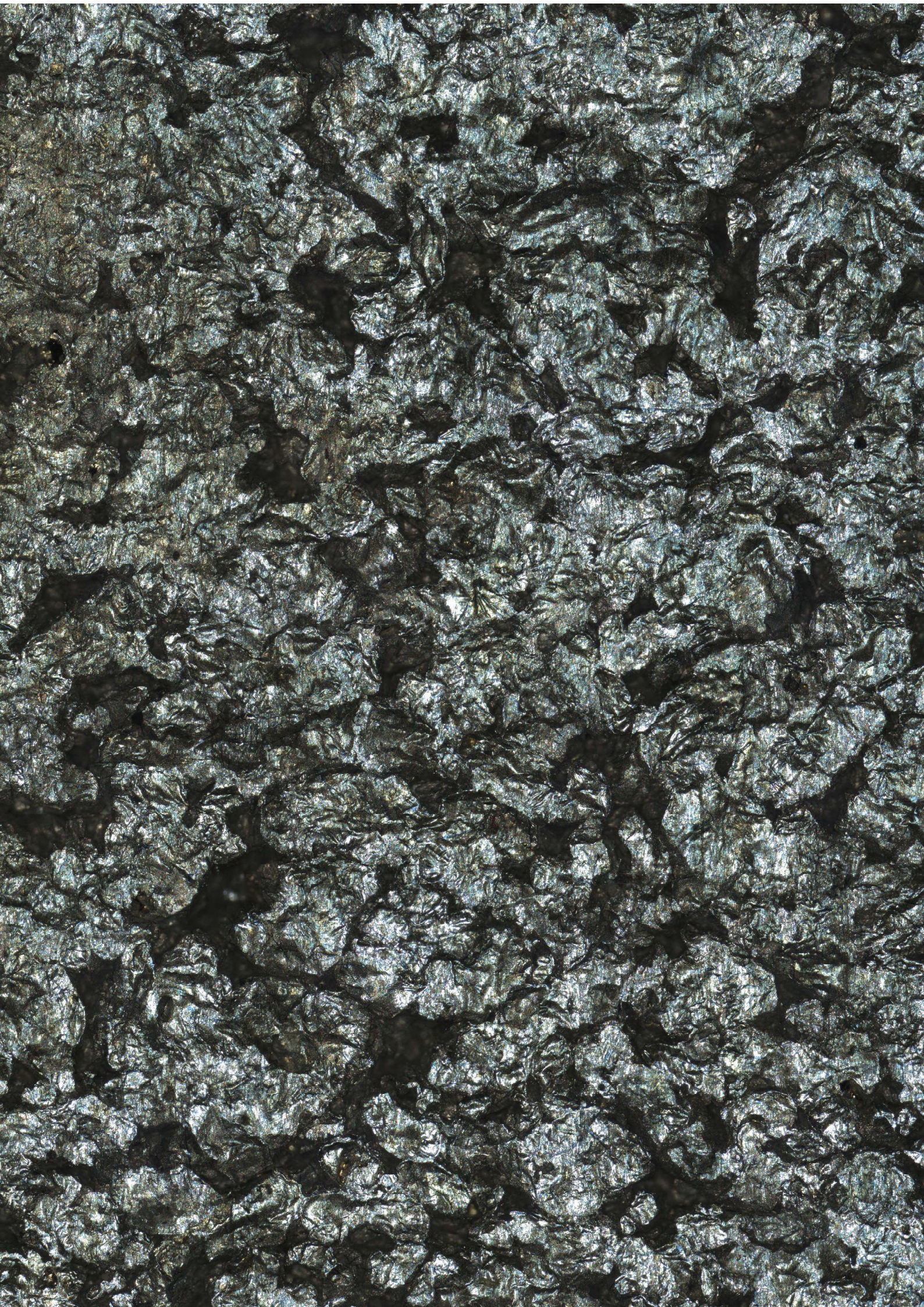
compaction temperature can be applied to overcome deformation. This will soften the polymer and will reduce deformation after release from the mould. The durability of the samples is poor, especially for foils have low aluminium content. Techniques to enhance the mechanical properties of the samples have to be researched. The

Figure 7.18: *Compacted sample material | Strings | 110*

(a) S1.S.CH **(b)** S2.S.CH

Note: String granulates of different sample materials compressed at 230 MPa at 110°C.

pallets pressed from sample material S1 have high polymer content (and therefore low aluminium content). Recovery of aluminium from this material is very inefficient. However, due to the low aluminium content this material could potentially be recycled as a plastic instead.



7.3

Polymer interaction & sintering capabilities

This chapter describes a series of experiments to get a better understanding of the characteristics of aluminium polymer foils when introduced to elevated temperatures. The samples produced in the previous experiment are introduced to elevated temperatures to create a more robust material that is more suitable for an architectural application. By binding the aluminium particles, a more stable material should be achieved.

The experiments are described in chronological order. However, some experiments were carried out in parallel.

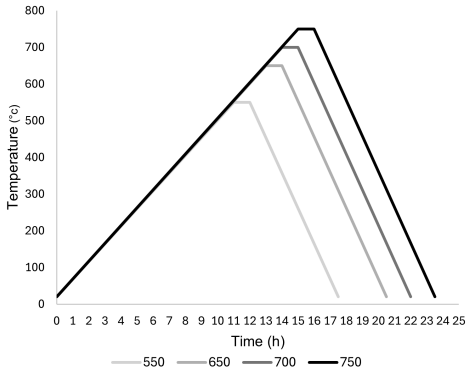
Experiment 1

This first experiment is used to understand the material and get a rough estimate of material behaviour under elevated temperature.

Heating

Different sample materials are shred to a small granulation size and slightly compacted and are placed in a crystalcast (Goodwin Refractory Services LTD Crystalcast) mould. This mould is described in section 7.4. The mould is placed in the oven (Rohde ELS 200s oven) and heated using the firing schedules shown in figure 7.19. The sample are heated in air environment, with 50 °C increments per hour up until a set-point of 550 °C, 650 °C, 700 °C and 750 °C. The specimen is held at the set-point for 60 minutes. Afterwards the oven is turned off and the specimen is let to cool up until room temperature with a step size of approximately 100 °C per hour.

Figure 7.19: *Firing schedule | Experiment 1*



The goal of the experiment is to get a rough understanding of material behaviour on different elevated temperatures. The samples will be checked for left over polymer, carbon deposit, oxidisation and carbonisation. Also, the minimum temperature to melt the aluminium in the specimen will be found to set a benchmark for further testing. As a reference a clean piece of aluminium is placed in the oven together with the aluminium composite sample material.

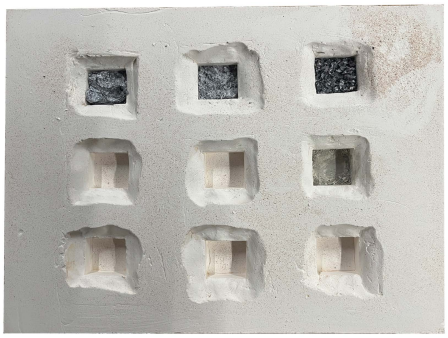
Results

The fired sample are shown in figure 7.20. For all temperatures in the experiment the were no visual remainders of polymer in the specimen. There was however some sort of deposit on the aluminium, showing as a dark grey surface on the aluminium shreds. There was also a white substance left in the mould which could be aluminium oxide. For all temperatures there was no sign of connection between the different aluminium particles. The compressed samples (at 230 MPa) showed better results than the non-compressed samples.

Conclusion

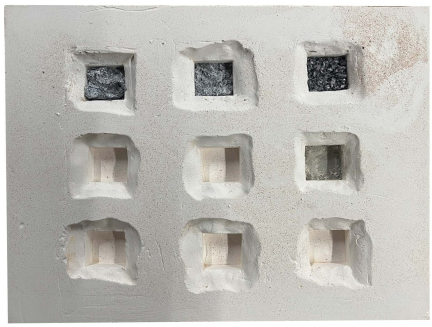
The firing of the non-compacted samples did not show promising results. The deformation of the pure aluminium shows that the temperature was however high enough to melt the pure aluminium. The question is why the other samples did not show signs of melting or connection between aluminium particles. An option could be that the amount of aluminium in the samples was too low. Another interpretation of these results could be that most of the aluminium in the composite formed aluminium oxide or aluminium carbide.

Figure 7.20: *Results | Experiment 1*

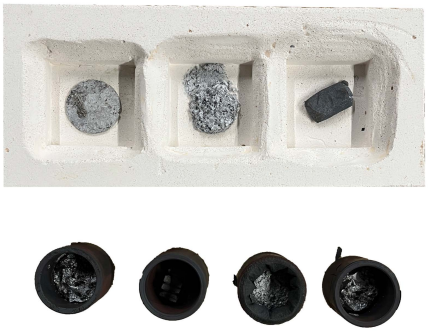


(a) Firing result 550 °C

(b) Firing result 650 °C



(c) Firing result 700 °C



(d) Firing result 750 °C

Experiment 2

To minimize the possible formation of aluminium oxidation a faster heating method was studied. While heating in an oxygen-limited environment would have been more effective in preventing oxidation, this approach was not feasible due to limitations in available experiment. Therefore, instead of placing the mould and sample in the oven before turning on the oven, in this experiment the sample was placed in and oven that was all ready at the targeted temperature. The Rohde ELS 200s oven has a large door, which would release a lot of heat when opening during operation. For this reason, the Carbolite Gero HTF 1700 was used for this experiment. The crystalcast mould used in the first experiment was not compatible with these large temperature difference. Therefore, a steel mould was fabricated to place the sample in.

Heating

The oven was initially set at a temperature of 750°C. During testing the temperature was increased to 850°C. The specimen was kept at this temperature for 20 minutes and was then removed from the oven to cool at room temperature (20°C). The hold time and temperatures were based on temperatures used in experiments from Nayak et al., 2022 and Papantoniou et al., 2018.

Compressing

15-gram sample of sample S2 were compressed at 230 MPa and placed in the steel moulds. The samples tended to deform after compression. Therefore, they were placed in the mould directly after compression. During this test the compaction was not relevant because the desired result was not to bind the aluminium particles, but simply to see if the aluminium would show less oxidation if heated faster.

Results

After firing samples from S2 did not show connection between the aluminium granules. Also, these sample showed a white substance. Initially the assumption was made that the aluminium had oxidised and gave this white appearance. An attempt was made to reduce by this by heating faster and for a shorter time. This however did not seem to make any difference. To verify this hypothesis an XRD analysis was performed to check for Al_2O_3 formation. The results of the XRD analysis indicated no evidence of major aluminium oxidation. This means the heating speed is for this part of the research not of importance. Instead, the white appearance can be traced back to the presence of calcium carbonate (calcite)($CaCO_3$) and calcium oxide (lime)(CaO), as shown by the XRD analysis (table 7.5. The full result of the XRD can be found in appendix C. Calcium carbonate is used as filler material in polymers as described in chapter *Material*. The calcium oxide is a result of the decarbonation of the calcium carbonate.

Table 7.5: *XRD analysis of S2 and S4 samples*

Sample	Compound	
S2 650-700-750	Aluminium	Al
	Lime	CaO
	Calcite	$CaCO_3$
S2.F.CR 750	Aluminium	Al
	Lime	CaO
	Calcite	$CaCO_3$
S4 650-700-750	Aluminium	Al
	Silicon	Si

Note: XRD results of sample S2.P.CR, S2.F.CR and S4.F.CR.

Conclusion

The results of the XRD indicate that there is no reason to assume that major oxidation of aluminium is occurring. The filler material used in this specific polymer could be the reason there is little to no connection between aluminium particles in the sample.

Experiment 3

To gain more information on the influence of the polyethylene on the melting of the aluminium a set of samples was pressed with increasing amounts of polyethylene contamination. Clean aluminium was sourced from aluminium machine shavings. These shavings were assumed to be clean and 100% aluminium. The polyethylene contamination was modelled by mixing different amounts of sample S2 in the aluminium shavings. The different mixture ratios are noted in table 7.6.

Table 7.6: *Pressed pallets | Aluminium polyethylene contamination*

Sample	Shavings (g)	S2 (g)	PE content %
Al.100.0	15,0	0,0	0
Al.90.10	12,9	2,1	10
Al.80.20	10,9	4,1	20
AL.70.30	8,8	6,2	30
Al.60.40	6,7	8,3	40
Al.50.50	4,7	10,3	50

Note: Mixing ratios based on 100% aluminium content of shavings and 27,5wt% aluminium in sample S2.

Compressing

The samples were compressed at 230 MPa. The samples are shown in figure 7.21. After compressing they are placed in the steel moulds and placed in a preheated oven as described in experiment 2. The samples all show a high amount of compaction after compressing. The compaction is estimated at 95%, decreasing in small steps when increasing polyethylene contamination.

Heating

Sample Al.100.0 and Al.90.10 were fired for 15 minutes at 850°C. After not showing the desired results samples Al.80.20 and AL.70.30 were fired at 880°C for 15 minutes. The last samples (Al.60.40 and Al.50.50) were fired at 920°C for 15 minutes. The results after firing are shown in figure 7.22.

Results

The samples with higher aluminium content showed clear melting of the aluminium. The lower the aluminium content in the sample, the more white substance was found and the less solid the sample became. The sectioning results of these samples are shown in figure 7.23.

The saw marks on the samples complicate the interpretation of the section surface. The samples with higher polyethylene contamination show porosity in the core of the sample.

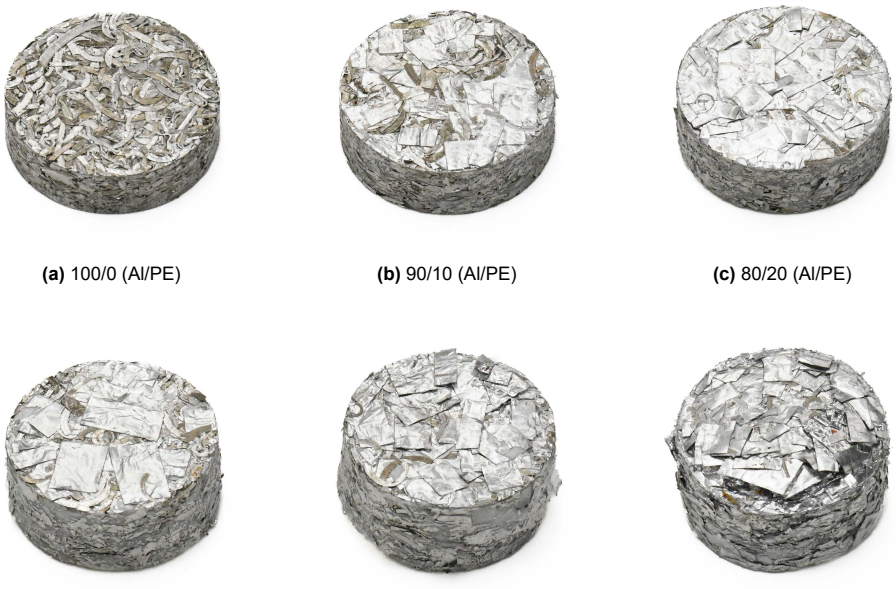
As the section views show, a brittle layer of oxidised aluminium floats on top of an apparently solid layer of aluminium (Al.100.0). This same principal shows in the with polyethylene contaminated samples. The layers are not well bonded and can be separated with pliers or tweezers. Sample Al.60.40 shows lamella structure porosity in the core of the sample. This can be caused by longitudinal polymer shreds. All samples show traces of molten aluminium on the surface of the sample. Thick oxide layers can be found locally.

Conclusion

The polymer contamination causes cavities in the aluminium. This can be interpreted as the polymer functioning as a spaceholder as described in chapter 6.

A crust of oxidised aluminium appears on all samples. This is not or not only induced by the contamination. Reasons for this crust could be interaction between the steel mould and the sample outer layer. Using silver steel for the mould instead of low-quality steel could be used to check this hypothesis.

Figure 7.21: *Aluminium samples with polyethylene contamination | virgin samples*

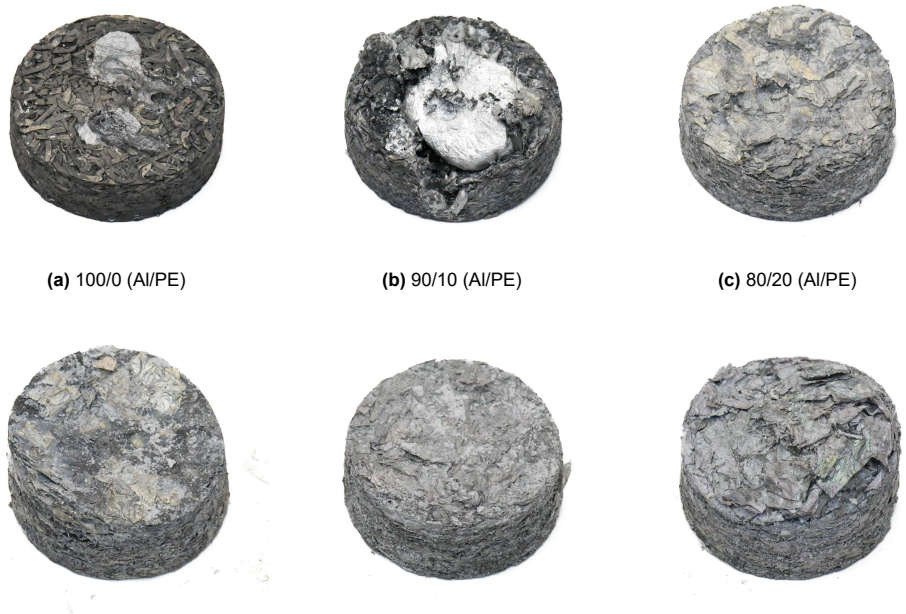


(a) 100/0 (Al/PE) **(b)** 90/10 (Al/PE) **(c)** 80/20 (Al/PE)

(d) 70/30 (Al/PE) **(e)** 60/40 (Al/PE) **(f)** 50/50 (Al/PE)

Note: Samples with different amount of polyethylene contamination.

Figure 7.22: *Aluminium samples with polyethylene contamination | fired samples*

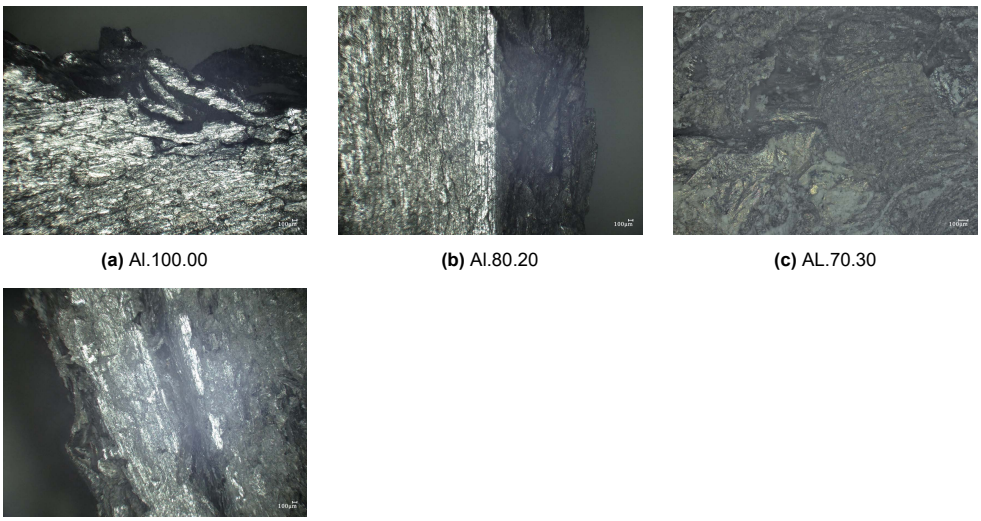


(a) 100/0 (Al/PE) **(b)** 90/10 (Al/PE) **(c)** 80/20 (Al/PE)

(d) 70/30 (Al/PE) **(e)** 60/40 (Al/PE) **(f)** 50/50 (Al/PE)

Note: Results of fired samples with different amount of polyethylene contamination.

Figure 7.23: *Section view of polyethylene contaminated aluminium samples*



(a) Al.100.00 **(b)** Al.80.20 **(c)** AL.70.30

(d) Al.60.40

Note: Section view of cut samples Al.100.0, Al.80.20 and Al.60.40 made with Keyence VHX-7000 microscope at 100x magnification.

Experiment 4

After the XRD analysis (experiment 2) of the fired samples pressed from sample material S2 showed CaCO and $CaCO_3$ several samples of sample material S7 (in previous experiments fired to 750°C) were placed in a stack of sieves (figure 7.24. The stack consisted of the following sieve sizes: pan, 0.125mm, 1.0mm and 2.00mm. After sieving for 10 minutes at an amplitude of 2.00mm at the Retsch sieve shaker AS 200. The pan showed a large amount of white substance. The material in the sieves above did not (visibly to the eye) show white substance.

An x-ray fluorescence (XRF) analysis was performed to determine the composition of the sieved material. The results of the XRF analysis are shown in table 7.7 and 7.8. Complete documentation of the XRF can be found in appendix C.

Compaction

The material remaining in the 1.0 mm sieve was placed in the die press and compacted at 230 MPa. The samples show very low porosity after compaction. Only very small traces of the granules can be found at the surface and bottom. The sides of the compressed sample are even more smooth. Sample S2 shows small dark grey spots on the surface, these are steel contaminations from the mould when the material was thermally disengaged in a previous step.

Heating

Afterwards the pallet was heated at 920°C for 10 minutes. The virgin pallet is shown in figure 7.26(a) and the fired pallet in figure 7.27(a). The fired pallet shows to be relatively firm and gives a promising appearance. The same experiment was performed for sieved samples of S5 7.26(b), S6 7.26(c) and S7 7.26(d). For these samples the oven was set to 750°C with 5°C/min and dwell for 60 minutes. After this the oven was turned off. The firing schedules are shown in figure 7.25

Figure 7.25: *Firing schedule | Experiment 6*

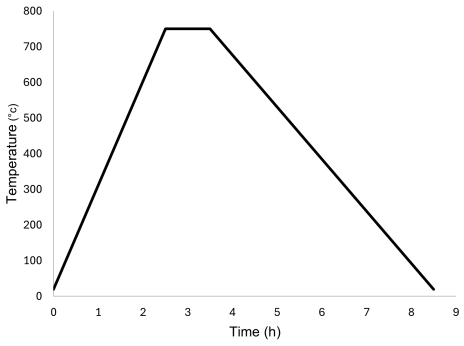


Table 7.7: *XRF analysis of S7 sieved material*

Sample	Compound	wt%
S7	Si	48.007
	Al	32.988
	Mg	13.878
	Fe	2.789
	Ca	1.491
	Zn	0.224
	Cu	0.141
	P	0.128
	S	0.120
	K	0.060

Note: XRF results of sieved sample S7.

Table 7.8: *XRF analysis of S7 sieve residue*

Sample	Compound	wt%
S7	Al	84.037
	Si	11.050
	Fe	2.522
	Mg	1.967
	Ca	0.142
	Ti	0.048
	Zn	0.044
	P	0.039
	Cu	0.034
	Mn	0.031

Note: XRF results of sieve residue of sample S7.

Figure 7.24: *Sieves*

(a) Pan **(b)** 0.125mm **(c)** 1.0mm **(d)** 2.0mm

Note: Different sieve sizes used in the experiment. From left to right pan, 0.125 mm, 0.1 mm, 0.2 mm.

Figure 7.26: *Aluminium samples of S2, S5, S6, S7 | virgin samples*

(a) S2 **(b)** S5 **(c)** S6 **(d)** S7

Note: Thermally disengaged samples sieved before compression to remove filler materials.

Figure 7.27: *Aluminium samples of S2, S5, S6, S7 | fired samples*

(a) S2 **(b)** S5 **(c)** S6 **(d)** S7

Note: Results of thermally disengaged samples sieved before compression to remove filler materials.

Results

All samples were wet sanded using 600 grid sandpaper. The results are shown in figure 7.28. The dull grey layer on the surface on the surface of the fired samples can be easily removed. Underneath is a smooth surface showing with minor imperfections. Sample S6 (7.27(c)) shows small flakes on the surface. These can be traced back to uneven granulation. Also, sample S5, S6 and S7 showed a small dent on the surface that was touching the bottom of the mould. There is no clear reason for this occurrence.

The samples feel firm and less crumbly than before firing. What is interesting is that the samples were fired in square moulds with clearance all around the samples edge. To release the sample from the mould only a small amount of force with a screwdriver on the edge of the sample was needed. The samples act like cookies that do not need support of a mould when being fired. They keep their original shape.

Figure 7.28: *Aluminium samples of S2, S5, S6, S7 | sanded samples*

(a) S2) **(b)** S5 **(c)** S6 **(d)** S7

Note: Results of polished samples.

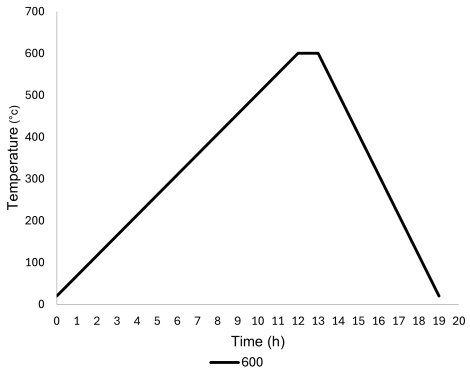
Conclusion

The method discussed above shows promising results. The samples are firm and raise high expectations for a potential architectural application.

Experiment 5

After finding promising results from compressing the sieved, already heated sample material a batch of thermally disengaged material was produced. 100 grams of S5, S6, and S7 were placed in steel curshables (pan) and heated in air environment with increments of 50°C per hour until the set point of 600°C. The material was held at the set-point for 60 minutes. Afterwards the oven was turned off and the material is let to cool up until room temperature with a step size of approximate 100°C per hour. The firing schedule is shown in figure 7.29.

Figure 7.29: *Firing schedule | Experiment 5*



Afterwards the material was sieved using the sieves from experiment 4. The material was sieved for 10 minutes at an amplitude of 2.00mm. This removes most of the carbon deposit and left over filler material. The sample material was stored in air tight bags.

Results

The workflow results in aluminium sample material with a reduced amount of contamination. The XRF analysis from experiment 4 shows that the method is effective to obtain over 80% pure aluminium.

Table 7.9: *Thermal disengagement effectiveness*

Sample	Compound	Conc.	After heating
S5	Al	72,1	91,5
	Si	21,5	5,5
	Mg	2,7	1,2
S6	Al	70,0	92,3
	Si	23,5	4,9
	Mg	2,7	1,2
S7	Al	76,8	89,9
	Si	17,0	6,8
	Mg	2,0	1,5

Note: Compound concentration in sample S5, S6 and S7 before and after heating. Full XRF data can be found in appendix C.

Table 7.10: *Thermal disengagement revenue*

	S5	S6	S7
Residual material	68,2	74,4	78,1
Original aluminium	70,2	74,8	79,6
Residual aluminium	65,2	71,5	76,6
Loss	5,0	3,3	3,0

Note: Revenue of thermal disengagement approach, measurements normalised to a value of 100 g (100%).

To confirm this assumption an additional XRF was performed for each of the sample material prior to heating and after heating and sieving. The results are shown in table 7.9. The results show that the average aluminium content was over 90% after cleaning.

The mass of the sample material was weight before heating. To compare the results among different sample materials the mass was normalised to 100 g. The results are noted in table 7.10.

As shown material is lost during the heating and sieving procedure. It is questionable whether these measurements are representative for the actual yield. The XRF results showed cleaning of the aluminium, but consistency was not checked. The samples with a higher original aluminium content show less loss of material than samples with a lower aluminium content. If a material with a lower aluminium content were to

be treated, even higher losses were to be expected, making the process less effective.

Experiment 6

The previous experiment showed an effective workflow and recipe to form a firm sample of aluminium. The pressure used in the experiment was 230 MPa. This is a very high compressive force equal to 20.000 kg. With scalability and produce-ability in mind it is valuable to check the effect of lower compression on the sample outcome.

Granulation

The thermally disengaged sieved material (from experiment 5) of sample material S5, S6 and S7 was granulated to powder size and 5 grams of sample material was put in the press.

Compaction

The same setup is used as in experiment 5, but now, the samples are not compressed at 230 MPa, but at a much lower, 100 (8700 kg) and 50 MPa (4300 kg). The compressed samples are shown in figure 7.30.

Heating

The samples were placed in the Carbolite Gero HTF 1700 at room temperature and heated at 5°C/min increments and kept at 750°C for 1 hour. After the heating is done the oven is turned off and the sample are slowly cooled to room temperature.

Results

Before heating the samples looked less compacted than the samples compressed at higher pressure (figure 7.30). Especially the samples compressed at 50 MPa showed a lot of texture from the shape of the granules. Also, the samples compressed at lower pressure are taller than the samples compressed at high pressure. They feel more brittle and crumblier and should therefore be handled with more care.

After firing at 750°C (figure 7.32) the samples turned out relatively firm. However, with less compression the samples became more brittle. The surface of the samples shows little ball shaped aluminium bubbles. These bubbles are the result of molten aluminium seeping out of the compressed sample via non compacted cracks in between particles.

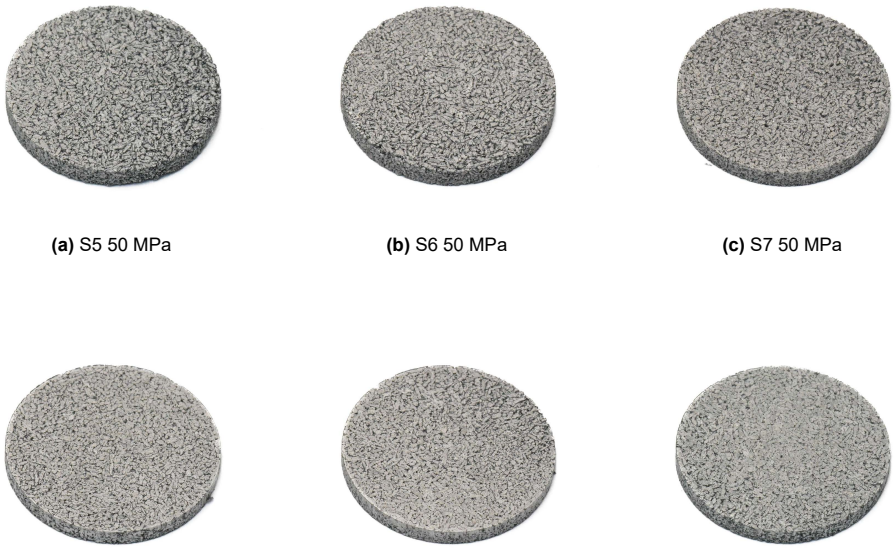
The same experiment was repeated but this time at 700°C to check the effectiveness of aluminium particles binding. The results are shown in figure 7.32. The samples show similar results to the once that were fired at 750°C. They seem to be more brittle than the samples that were fired at the higher temperature.

The surface textures changes when the specimen is compressed with higher force. Samples compressed at 50 MPa show a lot of texture on the surface, as a result of the shape of the granules. When the force on the surface is increased the surface becomes smoother. This is shown in figure 7.31.

Conclusion

The samples show different outcomes due to varying compaction and heating temperature. To verify effect on the material strength further testing has to be conducted.

Figure 7.30: *Samples of S5, S6, S7 | varying compression | virgin samples*

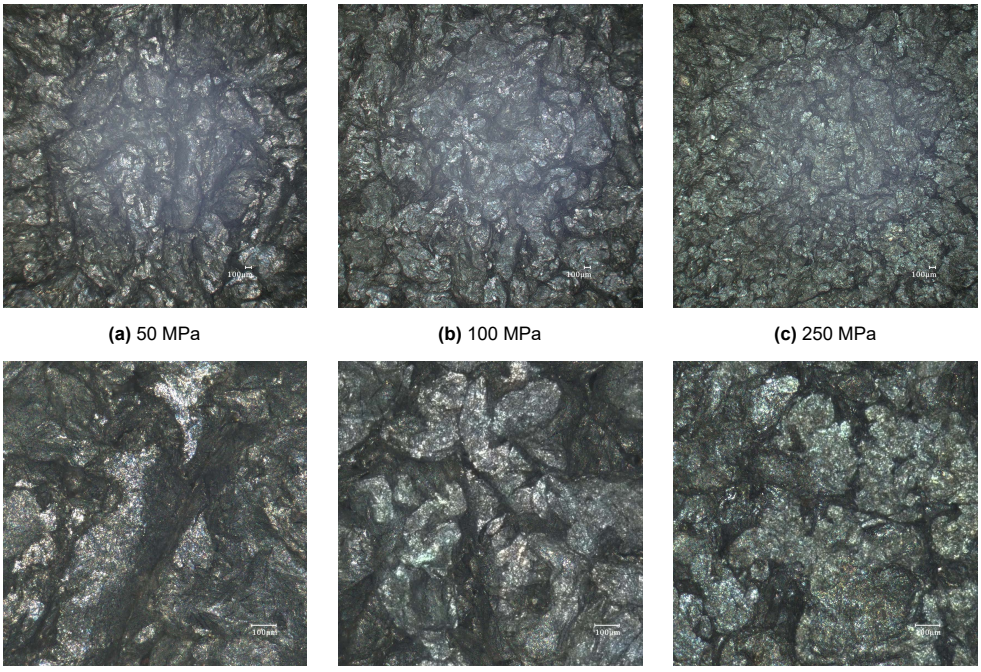


(a) S5 50 MPa **(b)** S6 50 MPa **(c)** S7 50 MPa

(d) S5 100 MPa **(e)** S6 100 MPa **(f)** S7 100 MPa

Note: Thermally disengaged sample material, powder (S5, S6, S7) compacted at 50 MPa or 100 MPa.

Figure 7.31: *Fired samples surfaces as a result of different compressive force*



(a) 50 MPa **(b)** 100 MPa **(c)** 250 MPa

(d) 50 MPa **(e)** 100 MPa **(f)** 250 MPa

Note: Surface texture of different thermally disengaged sample material compacted at 50 MPa, 100 MPa or 250 MPa fired at 750°C. (a, b, c) 50x magnification and (d, e, f) 200x magnification. Images made with Keyence VHX-7000 microscope.

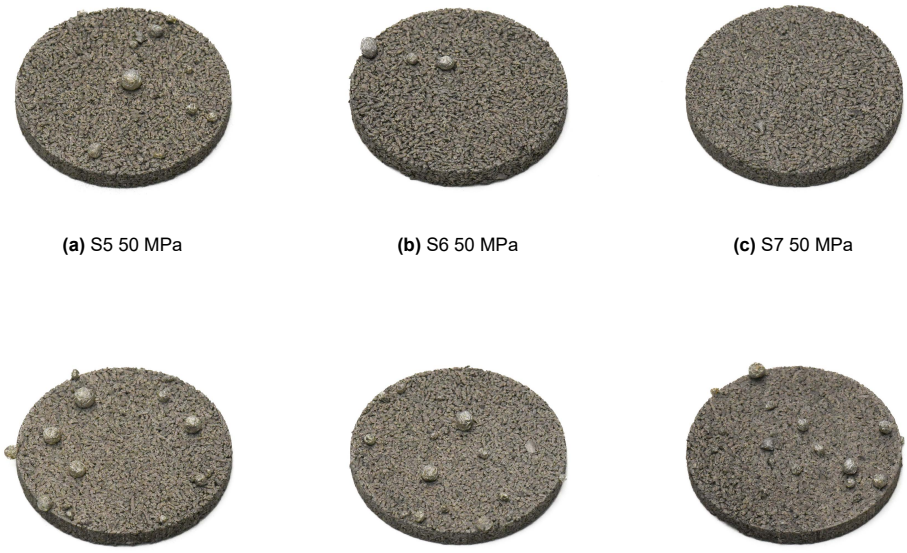
Figure 7.32: *Samples of S5, S6, S7 | varying compression | fired samples*

(a) S5 50 MPa **(b)** S6 50 MPa **(c)** S7 50 MPa

(d) S5 100 MPa **(e)** S6 100 MPa **(f)** S7 100 MPa

Note: Thermally disengaged sample material, powder (S5, S6, S7) compacted at 50 MPa or 100 MPa, fired at 750°C.

Figure 7.33: *Samples of S5, S6, S7 | varying compression | fired samples*



(a) S5 50 MPa **(b)** S6 50 MPa **(c)** S7 50 MPa

(d) S5 100 MPa **(e)** S6 100 MPa **(f)** S7 100 MPa

Note: Thermally disengaged sample material, powder (S5, S6, S7) compacted at 50 MPa or 100 MPa, fired at 700°C.

Experiment 7

The thermally disengaged material produced in experiment 5 was used for this experiment. This experiment will produce a set of beam shaped samples as a practice to produce rectangular sample and to eventually perform bending tests on.

Granulation

Before grinding the sample, material was run through the blender once more to reduce the size of the shreds. Due to the absence of the polymer layer at this stage the shredding was more effective than the initial results discussed in chapter *Size reduction & pallet pressing*. Also, no water was added to the blender. The material was granulated using the grinder and sieved to <2mm.

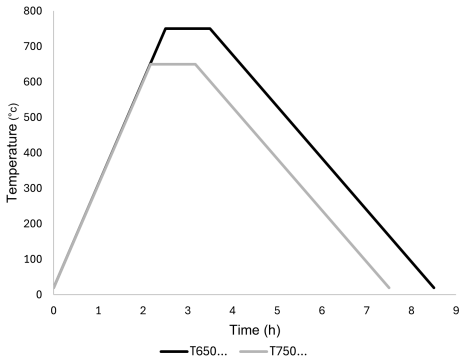
Compaction

To verify the effect of the parameters used in experiment 6, a set of samples is prepared to test in a 3-point bending test. For this test 15-gram samples are pressed. With testing in mind, the mould was changed to a beam shaped mould (10x20x50mm), instead of a circular mould. Further information about the mould can be found in chapter *Moulds*. The 15-gram samples consist of an equal mix of sample material S5, S6 and S7 (5 grams each). This mixture was preferred over a homogenous sample material as it more closely resembles a real-world situation. The samples were compressed at 100 MPa and 230 MPa.

Heating

The samples were placed in the oven at room temperature (20°C). The oven was heated with 5°C/min and held at 700°C and 750°C for 60 minutes. The firing schedules are shown in figure 7.34. After this time the oven was turned off. The samples are also noted in table 7.11.

Figure 7.34: *Firing schedule | Experiment 7*



Results

The sample showed similar results as the circular compressed sample from previous experiments. Figure 7.35 shows an overview of the different samples and there fired results. The sample produced at lower pressure (150 MPa) show a crumbly non compacted result at the bottom corners of the sample. Also, some leakage of material can be noticed on the edges of the specimen. There is also a gradient in compaction noticeable in the beam. The question is whether this gradient is through the whole beam or only on its outer surface. The samples compressed at 200 MPa show far less gradient of compression. Samples compacted at 250 MPa almost no gradient.

After heating the sample show the same balls of aluminium, seeping out of the specimen.

Conclusion

The mould shows to be functional and able to produce rectangular shaped sample. Where with the round sample crumbling occurred mostly on the surface, the crumbling now seems to collect in the bottom corners of the mould. A solution is to fill the mould more in the corners. Another solution would be using isostatic pressure.

Table 7.11: *Pressed beams from thermally disengaged sample S5, S6 and S7*

Sample	Grain size	Compaction (MPa)	Temperature (°C)
B.150.700	Powder	150	700
B.200.700	Powder	200	700
B.250.700	Powder	250	700
B.150.750	Powder	150	750
B.200.750	Powder	200	750
B.250.750	Powder	250	750

Note: Different sample recipes for beam shaped samples.

Figure 7.35: *Beam samples | varying compression and heating*

(a) 150 MPa **(b)** 200 MPa **(c)** 250 MPa

(d) Fired at 700°C, 150 MPa **(e)** Fired at 700°C, 200 MPa **(f)** Fired at 700°C, 250 MPa

(g) Fired at 750°C, 150 MPa **(h)** Fired at 750°C, 200 MPa **(i)** Fired at 750°C, 250 MPa

Note: Thermally disengaged sample material, powder (S5, S6 and S7) compacted at 150 MPa, 200 MPa or 250 MPa, fired at 700°C or 750°C.

7.4

Moulds

Mould outline

This section describes a number of different moulds used in various experiments. Moulds are used to give support to the sample as it is heated in an oven. The mould is used to hold the material together when temperatures rise above the melting point. Some moulds are used when compressing sample material, prior to heating.

Crystalcast mould

A mould is made from crystalcast (Goodwin Refractory Services LTD Crystalcast). The negative is made from 25mm x 25mm blocks of melamine wood. The wood is covered with clear tape and covered in a thin layer of Vaseline petroleum jelly to help release from the mould. The wood blocks are glued to the table with clay. The crystalcast is mixed in a ratio of 1 part water to 2,8 parts of crystalcast. The mixture is poured into the formwork and left to cure at room temperature for half an hour before the formwork is removed. The mould is rinsed of with warm water (40 °c) and left to dry overnight.

Figure 7.36: *Crystalcast mould*

Note: Crystalcast mould for three 25x25mm specimens. Used to heat specimens in oven.

Steel mould

A steel mould is milled on a lathe. The internal diameter is conveniently slightly larger than the diameter of the die used in the hydraulic press (ø 33mm). The mould has a 5 mm thick wall and base to prevent burning through at elevated temperatures (figure 7.37).

Figure 7.37: *Steel mould*

Note: Round steel mould for one specimen (ø 33mm), giving support during heating.

A square mould was also tested to make it easier to remove the specimen from the mould. Some samples did not require the support of a mould. A square mould leaves a gap when a round sample is placed inside. This gap can be used to pry the specimen out of the mould after firing (figure 7.38).

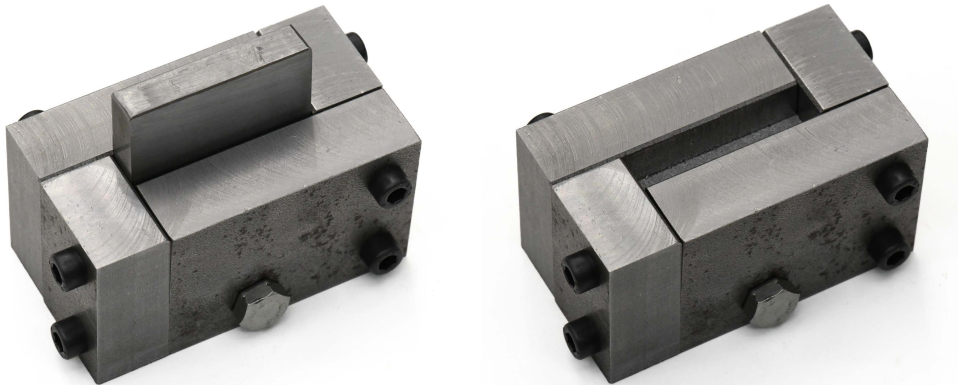
Steel (beam) mould

A beam shaped mould has been designed for pressing beam-shaped sample. The mould is made of silver steel to reduce potential interaction between the steel and the aluminium. Technical drawings of the mould can be found in appendix E. As shown in figure 7.39 the mould consists of six parts. Four interconnecting side pieces, a bottom piece and a compression piece. The mould is made on a milling machine, and the surfaces are polished to spec to ensure the dimensions are within tolerances.

Figure 7.38: *Steel mould*

Note: Square steel mould for one sample (ø 33mm), giving no support during heating, but collection material in case of melting.

Figure 7.39: *Beam shaped steel mould*



(a) **(b)**

Note: Figure (a) showing the steel mould with the compression piece inside. Figure (b) showing the mould without the compression piece, pressed beam sample visible.

8

Validation and application

Application

In order to give a purpose to the materials created in the previous section multiple applications within the building environment are being researched and designed. The experimental phase has shown that the results are promising but give little insight into the mechanical and physical properties of the material. This section will focus on verifying a certain set of properties of the material to find suitable applications within the building environment. The properties found will be used as input to Granta Edupack to check comparable materials (other than aluminium) to give a broader reference of architectural material applications.

Properties

Material properties for materials used in the building environment are commonly assessed using the following categories of criteria (Material properties, 2025)(ANSYS, Inc., 2023): Mechanical properties, thermal properties, hygrothermal properties, durability, aesthetic qualities and processability. All these categories can be described by different properties.

For this material validation a selection is made from the criteria used by ANSYS, Inc., 2023. Only some mechanical properties will be defined based on tests performed, some values will be referenced from the material datasheet from Ansys. Properties that are likely to differ from the values found in Ansys but not confirmed by testing, are not included in the validation.

Mechanical properties

To get a better understanding of the designed material and to be able to compare it with other commonly used materials in the build environment, a three-point bending test is performed for on a given set of specimens to measure the transverse rupture strength of the material. A three-point bending test was preferred over a four-point bending test due to the ability to handle smaller specimens.

The samples produced in experiment 6 were placed in the testing set-up. For each set of parameters five identical samples were produced to reduce the likelihood of random error.

The samples are all oriented in the same direction with the top surface facing up and a course bottom face facing down. During the test the sample is supported at two points with a span of 40 mm. A load is applied at the centre of the sample. The load is increased until the sample breaks. An overview of the set-up is shown in figure 8.1. The American Society for Testing and Materials (ASTM) B528 protocol is used. The ASTM suggests protocol B925 for testing powder metallurgy specimens. However, due to the scale of the project and conceptual approach of producing the specimens this would make no scientific sense. Also, production requirements stated by protocol B925 could not be matched using the available equipment.

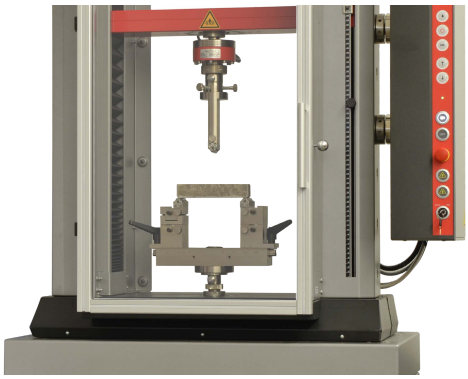
The bending test is performed on a ZwickRoell Z10 universall testing machine with . The setup is shown in figure 8.2.

To calculate the modulus of rupture the formula for a rectangular cross-section is used (eq.8.1).

$$\sigma_{TRS} = \frac{3FL}{2bd^2} \tag{8.1}$$

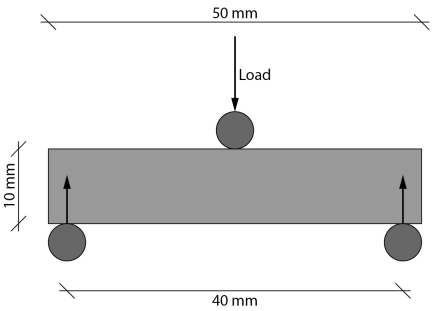
Where:

Figure 8.1: *3 point bending setup*



Note: 3 point bending set-up showing a ZwickRoell Z10 universal testing machine. ("ZwickRoell materials testing", 2025).

Figure 8.2: *3 point bending schematic*



Note: Standard 3 point bending set-up showing a 50 mm sample supported on steel supports spanning 40 mm resembling the setup used for conducting tests.

- σ_{TRS} = Modulus of rupture (MPa)
- F = Maximum applied force (N)
- L = Support span (mm)
- b = Width (mm)
- d = Depth (mm)

To calculate the flexural modulus is calculated using the formula shown in equation 8.2.

$$E_f = \frac{L^3 m}{4bd^3} \tag{8.2}$$

Where:

- E_f = Flexural modulus (MPa)
- m = Slope of the load-deflection curve (N/mm)
- L = Support span (mm)
- b = Width (mm)
- d = Depth (mm)

Results

Figure 8.3 shows an overview of all the samples used for testing. The results of the transverse rupture strength test described above are listed in table 8.1 and figure 8.4. The full data from the three-point bending test can be found in appendix F.

Table 8.1: *Flexural strength measured from different samples*

Sample	Flexural strength (MPa)	Flexural modulus (GPa)
B.150.700	8,14	0,75
B.150.750	8,03	0,49
B.200.700	12,54	0,75
B.200.750	19,94	0,86
B.250.700	17,14	1,44
B.250.750	36,61	2,09

Note: The numbers in this table are averages of 5 repetitive tests per sample set. Full testing data can be found in appendix F

Discussion

The samples produced in experiment 6 showed a gradient in the surface texture after compressing. This is an indication of uneven compaction. This could have affected the test results. Also, when placing the granulated sample material in the mould, the larger granules tend to float on top while the smaller granules sink to the bottom. Therefore, the granule mixture is not completely homogeneous throughout the sample.

The measurements of the test show a wide range of flexural strength within the supposedly identical set of samples. This indicates that there are wide variations between samples. In particular, samples B.200.750 and B.250.750 show large variations.

The flexural modulus is very low. It is questionable whether the measurement is accurate. It is possible that the actual bending modulus is higher but, this is not shown due to jack error.

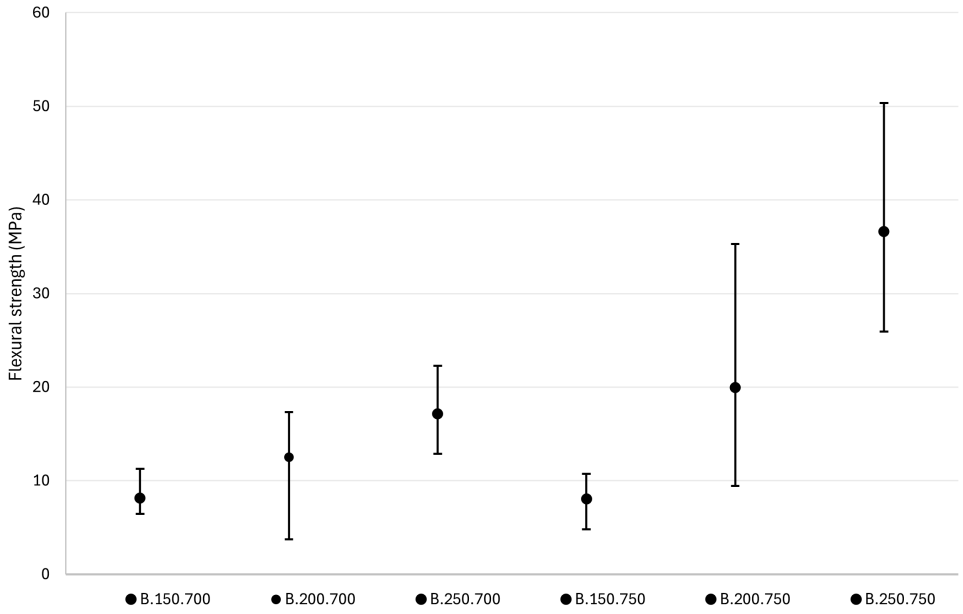
Microscope images of the three samples with lowest flexural performance and three samples with the highest flexural performance are shown in figure 8.6. It clearly shows that the better performing samples show more compaction and therefore less porosity. The best performing samples show 87% compaction compared to standard aluminium. The best three sample all came from sample set B.250.750. The least performing samples came however from sample set B.105.700, B.150.750, and B.200.700. Their average compaction came up to around 75%. The samples were all tested with their top surface facing upwards, this was the side that was most compacted in the gradient. The bottom side of the samples showed the least compaction. It is unclear what effect the testing orientation had on the measured flexural strength.

Graph 8.5 confirms this conclusion from the visual analysis, showing that higher density results in a higher bending strength. While there appears to be a correlation between these two values, there are many samples that differ significantly from this trend. This would suggest that there are other variables effecting the flexural strength of the sample.

Figure 8.3: *Overview of all samples from bending test*

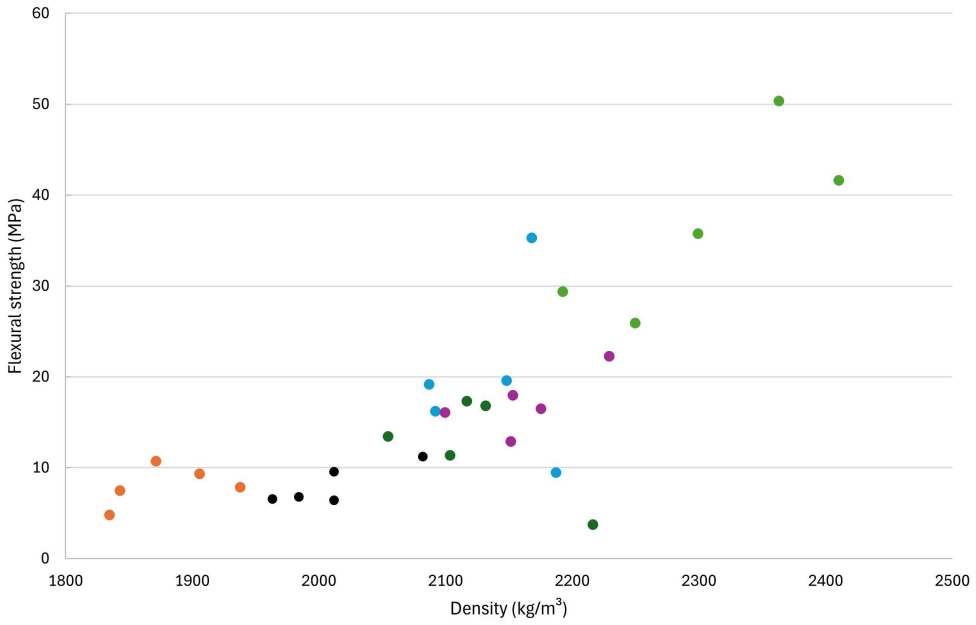
Note: Samples from the six different samples sets used in for testing.

Figure 8.4: *3 point bending test results*



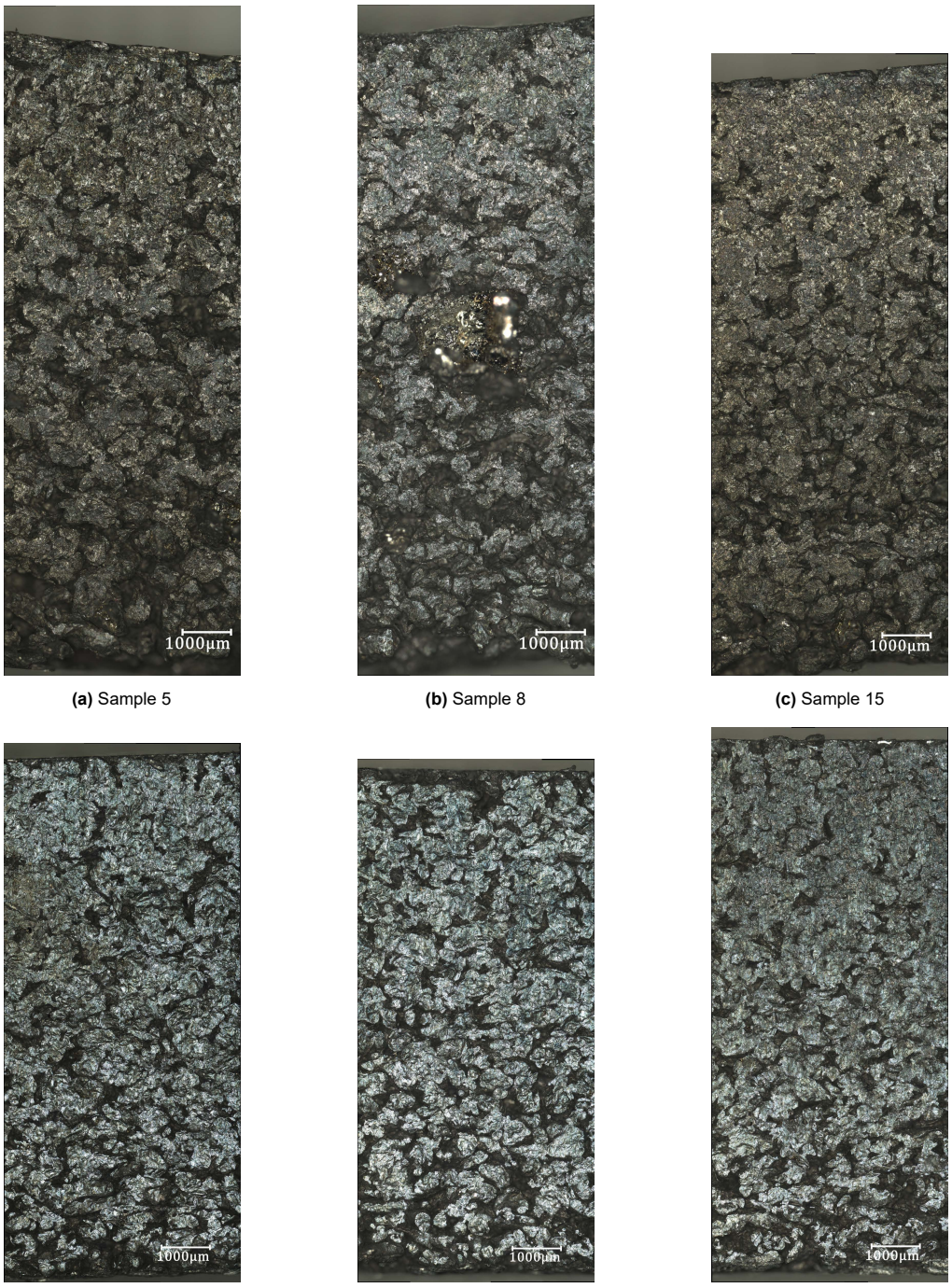
Note: The graph shows the average flexural strength (MPa) per sample set. Error bars show the minimum and maximum values observed.

Figure 8.5: *Bending strength compared to density*



Note: The graph shows the density compared to the bending strength of the tested beam shaped samples.

Figure 8.6: *Microscope section of beam samples*



(a) Sample 5 **(b)** Sample 8 **(c)** Sample 15

(d) Sample 26 **(e)** Sample 27 **(f)** Sample 30

Note: Section view of three least performing samples (8.6a, 8.6b, 8.6c) and best performing samples (8.6d, 8.6e, 8.6f).

Conclusion

The heating temperature for the samples compacted at 150 MPa does not have a significant result on the flexural strength of the samples. Both B.150.700 and B.150.750 performed equally well in the test. For samples compacted at 200 MPa and 250 MPa a higher heating temperature has a positive effect on the flexural strength of the sample. Lower compaction combined with a higher heating temperature (B.200.750) gives a better result than higher compaction combined with a lower heating temperature (B.250.700). The best performing set of samples were the samples compacted at 250 MPa and heated at 750°C.

Thermal properties

The thermal properties of the specimens are referenced from Edupack and are described as a good thermal conductor and non-flammable material. It is assumed that the sample material will give similar results if tested. Edupack describes a thermal resistivity ranging between 0,00435 - 0,00452 m.°C/W. The porosity of the material will have a positive effect on the thermal resistivity, resulting in a lower heat transfer efficiency.

Durability

The durability of standard aluminium is already stated as 'limited use' by Edupack. The durability of this material could technically be the same. However, all samples show to be brittle and less durable than standard aluminium. The surface finish can also vary, and a high consistency is difficult to achieve.

The UV durability is described as excellent and assumed to be unchanged by the proposed processing. The durability considering exposure to fresh and salt water is assumed to be unchanged.

Processability

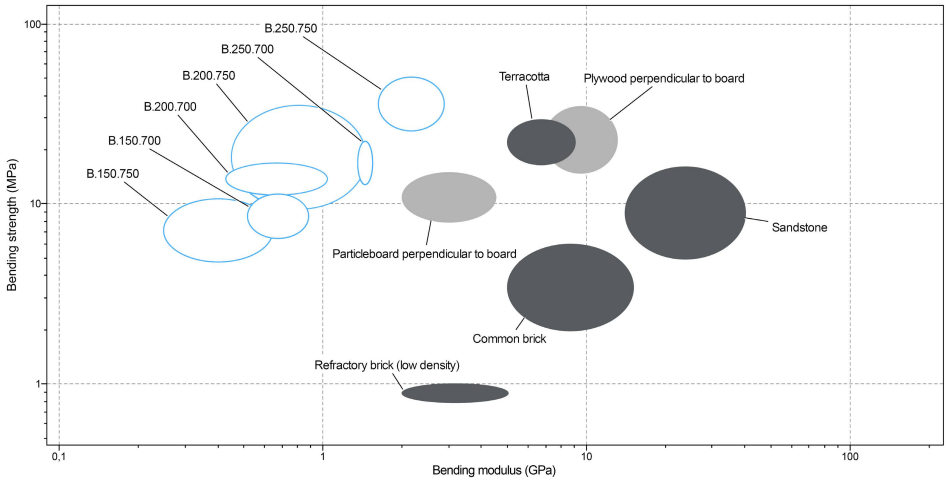
For all parameters it is possible to drill, cut, mill and polish the material. Also, after compressing the material green part can be removed from the mould and placed in the oven without the need of the support of a mould. This gives a lot of freedom in shaping the designed element.

Comparable materials

The material properties described above are used to find comparable materials, using Edupack. The comparison is made using the flexural strength and flexural modulus. Figure 8.7 gives an overview of a set of comparable materials. Relevant materials are highlighted. The flexural strength is comparable to plywood or terracotta. The flexural modulus however is much lower. This shows how brittle the aluminium is after heating.

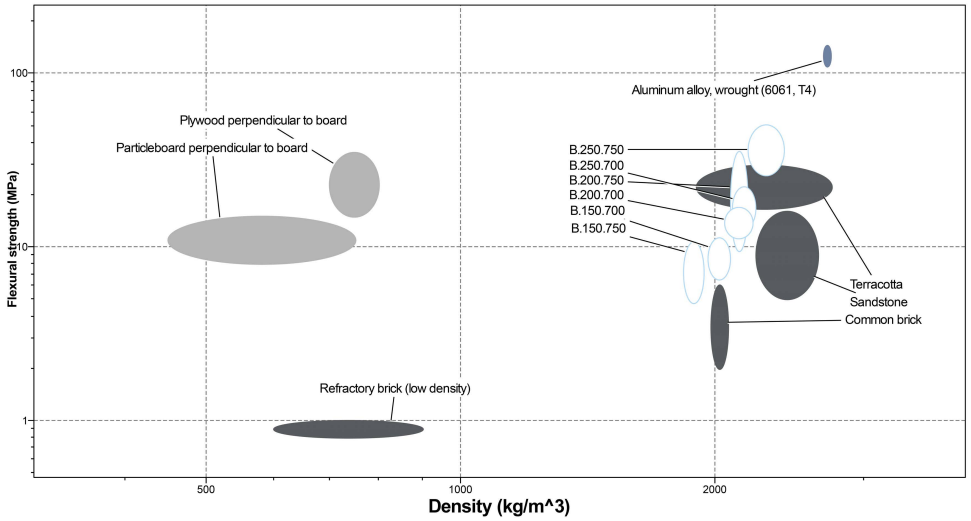
Figure 8.8 shows an overview of flexural strength compared to the density of the material. This shows again that terracotta is very comparable to the aluminium from sample B.250.750.

Figure 8.7: *Comparable architectural materials | flexural modulus*



Note: The graph shows a selected set of comparable material with architectural applications to give a reference for the found properties in this section.

Figure 8.8: *Comparable architectural materials | density*



Note: The graph shows a selected set of comparable material with architectural applications to give a reference for the found properties in this section.

Surface treatment and aesthetic qualities

Depending on the amount of pressure applied to the material before heating different surfaces can be achieved. Higher pressure will result in a smoother surface finish (figure 8.9a) whereas a lower pressure will show more texture from the original shape of the granules (figure 8.9b). For all levels of compression, the surface will have a smooth appearance from a distance, the character will show from up-close. Without surface treatment the surface will have a matt and grey appearance. However, after polishing the surface will have a reflective appearance (figure 8.9c). The surface of specimens compressed at lower pressure will show, after polishing, reflective parts where the surface has high spots and will show grey dots where the surface has lower spots (figure 8.9d). By polishing lightly, the surface character will be preserved. More intense polishing will result in a smooth finish, regardless of the amount of compression applied prior to heating.

Composites

While the mechanical properties of the thermally disengaged beams described above confirm that the result of the designed workflow can results in a firm material, the visual appearance of this material is less interesting. However, the specimens produced in the first experiments show interesting visual results but a lack of structural rigidity. Therefore, a combination of these different samples is produced using only heat.

Fired samples (5-gram TDE powder, heated at 750°C for one hour) similar to the samples from experiment 4 are placed back in the mould and a layer (5 gram) of shredded sample material from S1, S3, S4 or S7 is placed on top. Before the aluminium sample is placed in the mould, the contact surface with the other sample material is roughened scratching with a sharp object This is done to increase surface area for the polymer to adhere to. The mould is then heated in an oven to 200°C and compressed at 50 MPa. This temperature is commonly used to weld polyethylene. The sample and the mould are cooled under pressure. After cooling (< 50°C) the sample is removed from the mould. The results are shown in figure 8.10.

Depending on the application different compositions can be made by varying the layer thickness and layer orientation. For outdoor applications a composite can be made using an inner and outer layer of aluminium with a polymer layer in-between, creating a rigid panel. An example is given in figure 8.10d. Depending on the desired mechanical properties of the panel thicknesses can vary.

For indoor applications a less durable panel can be realised. Indoor applications are not substituted to frost, moisture or UV radiation. For visually focused applications a single layer of aluminium can be combined with a single or double layer of polymer. Examples are given in figure 8.10a, 8.10b and 8.10c.

Figure 8.9: *Surface finishes*

(a) Smooth untreated sample

(b) Untreated textured sample

(c) Polished sample

(d) Semi polished textured surface sample

Note: Different surface finishes based on compressive force and polishing techniques.

Figure 8.10: *Different composites combining visual quality with structural qualities*

(a) Composite of sample material S1 and aluminium backing

(b) Composite of sample material S7 and aluminium backing

(c) Composite of sample material S3 and aluminium backing

(d) Composite of sample material S1 with an aluminium front and backing

Note: Composites of different sample materials. Compressed at low temperature (~200°C) and a fired backing.

Application design

This section will give concept applications for the designed materials described above. The literature research discussed the 9R-ladder. This ladder describes the nine strategies that can be used to come to a circular economy. Recycling is one of the lower strategies. Designing for demountability is a strategy that has direct impact on the recyclability of a product or a building as a whole. When designing a construction system for buildings it is important to think about the reuse of construction elements. To increase the circularity of a building, 'dry' building systems are used. These systems use demountable connections between elements. The proposed applications bellow is designed in a way that they are suitable for demountability.

Surfaces as thermal heat exchangers

Based on the materials properties, it is evident that it is well-suited for sheets material applications. Its high thermal conductivity makes it particularly attractive for use in heat exchanging systems. Therefore, a thermal heat exchanging panel has been designed for application on outside building surfaces (facade) and inside building surfaces (flooring). This system can be used to heat the building during winter and cool the building during summer.

It is important to note that in both scenarios, additional energy input is required to achieve the desired temperature.

To enhance energy efficiency and overall system effectiveness an aquifer thermal energy storage system can be introduced to store the energy for later use.

Harvesting heat

The radiative heat from the sun can be captured and used to heat the building or to fill the aquifer thermal energy storage system. This system is most effective in summer, when there is strong radiative heat from the sun and higher outdoor temperatures. However, heat can also be harvested in winter. The system is the least effective in scenarios with no sun and very low outdoor temperatures (8.11a).

Harvesting cold

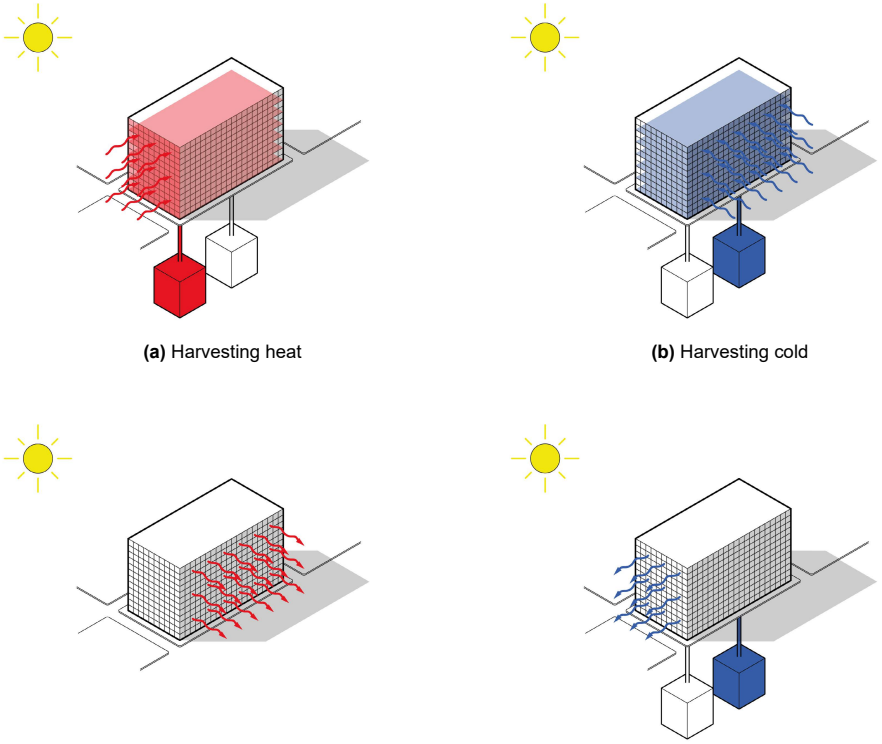
The shaded side of the building (the north side) can be used as to harvest cold. During winter, this system is highly effective to fill the aquifer. This side of the building can also be used to cool the inside of the building during spring, when the sun's radiation is strong but outdoor temperatures are still low (8.11b).

From another perspective harvesting cold can also be seen as removing heat as shown in figure 8.11c, where the facade functions as an exhaust to discard unwanted heat.

Urban heat island

A more experimental scenario of the system would be to cool the facade during the summer. The temperature of the facade increases during summer and even after sunset, it remains warm for a long time. Consequently, a lot of heat is retained in cities. This phenomenon is known as the urban heat island effect. Cooling the facade after sunset heat removes heat from the facade and reduces the urban heat island effect. Cooling the facade at the night during the summer would provide a greater thermal buffer for during the daytime (8.11d).

Figure 8.11: *Buildings as thermal heat exchangers*



(a) Harvesting heat

(b) Harvesting cold

(c) Facade as an exhaust

(d) Reducing urban heat island effect

Note: Different scenarios of the function of a thermal heat exchanging facade.

Surfaces as thermal heat exchanger | AluFlux

The scenarios described above make use of a heat exchanging facade and heat exchanging flooring system. The AluFlux panel has been designed to accommodate the scenarios described above. It is a thermal heat exchanger panel that can be used both outdoors and indoors. It uses the thermal conductivity of aluminium to efficiently exchange heat between water and air on exterior and interior surfaces. The following sections describe these panels in more detail.

Exterior facade panel

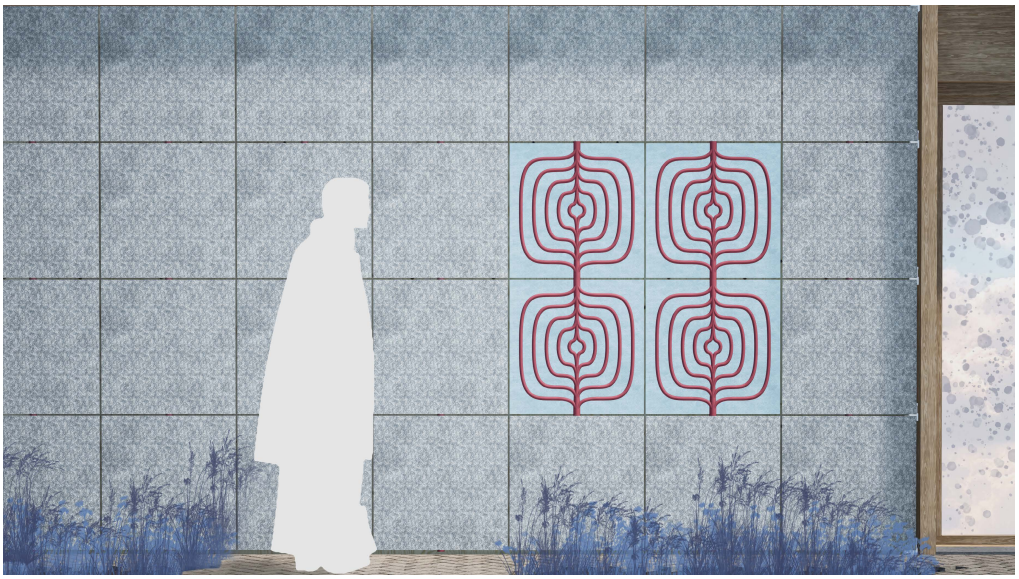
The aesthetic appearance of the non-heated aluminium foils combined with the firm backing of the cleaned aluminium can be used as an exterior cladding panel. The proposed design bellow takes advantage of the free formability of the powdered aluminium by using a shaped mould. The panels are lightweight and are estimated at a weight of 700 gram (300 x 300mm) or 3500 gram (600 x 600mm). An overview is shown in figure 8.12. More details about the weight estimation can be found in appendix H.

The AluFlux panel is built up from different layers. The face of the panel can be made out of non-treated aluminium composite foil. By shredding in different grain sizes, various results can be obtained. Behind this non treated layer is a firm layer of cleaned aluminium. This layer will act as a structural layer to create stiffness in the panel. The technical drawing is shown in figure 8.13.

A liquid (water) is pumped through the facade to transport thermal heat from the facade to the system. For now, a standard 600 x 600 mm panel is designed to accommodate standard building dimensions. On the top and bottom side of the panel is a connection point to connect panels to each other. After this connection point the thickness of the tube is reduced and split up in multiple smaller 'veins' creating a leaf like structure. By reducing the tube size, more surface area is in contact with the aluminium. Therefore, the liquid will exchange heat more quickly. The tubing could be placed in the mould before compressing or can be added on the back of the panel after pressing (8.14). A third option combines both methods, using a bolted connection between two panels to clamp the tubing between them.

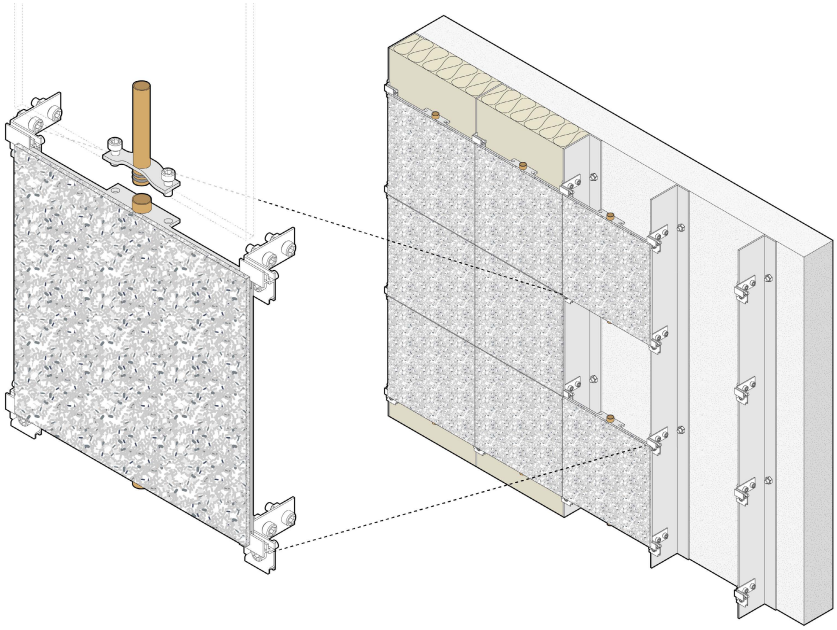
The connection between panels has to take some margin into account for placing error of the panel. This can be achieved by using a connection nipple as sketched in figure 8.15. The connection also has to be able to withstand the thermal expansion of the panel. For a panel of 600 x 600 mm, a temperature change of $\Delta 60°C$ would result in an expansion of 0.8 mm in both directions.

Figure 8.12: *AluFlux panel*



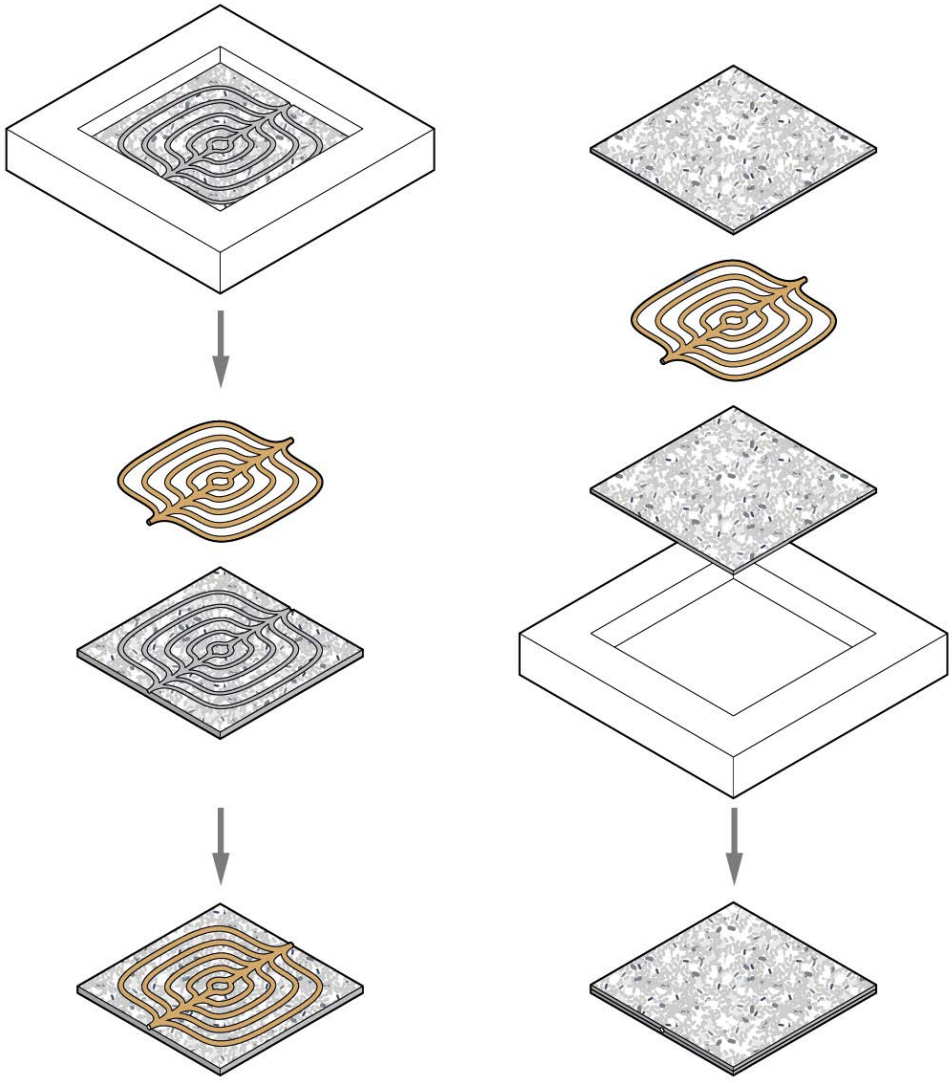
Note: The image shows a visual representation of the AluFlux panel applied in a facade. The tubes are shown in red to mimic the heated water being pumped through.

Figure 8.13: *Technical drawing facade panel*



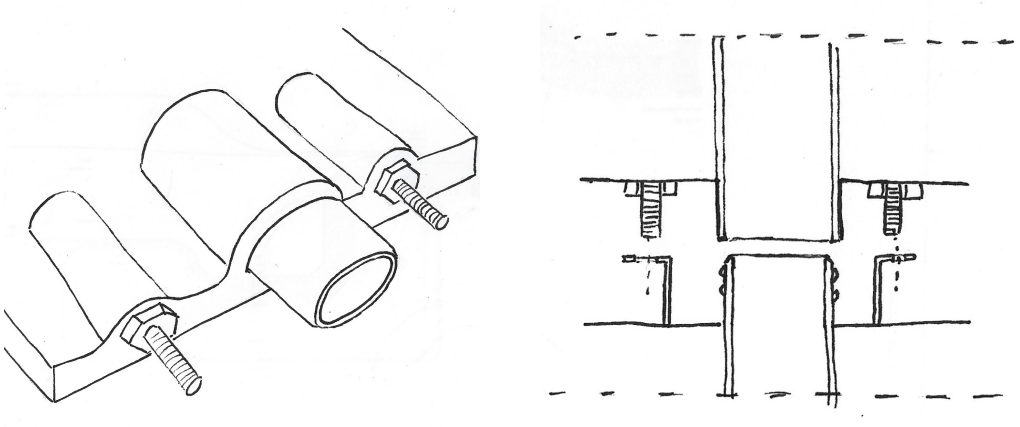
Note: The drawing shows the face of the panel. The drawing gives an impression of a potential mounting system of the panel.

Figure 8.14: *Facade panel production*



Note: Different production techniques to integrate tubing in to the panel. On the left side a panel is produced, and the tubing is added after pressing. On the right side the tubing is placed in the powder and compressed together, this way the tubing is fused in the panel.

Figure 8.15: *Connection detail sketch*



(a) Overview **(b)** Section

Note: The image shows a sketch of a potential connection between heating pipes of different facade panels.

Underfloor heating tile

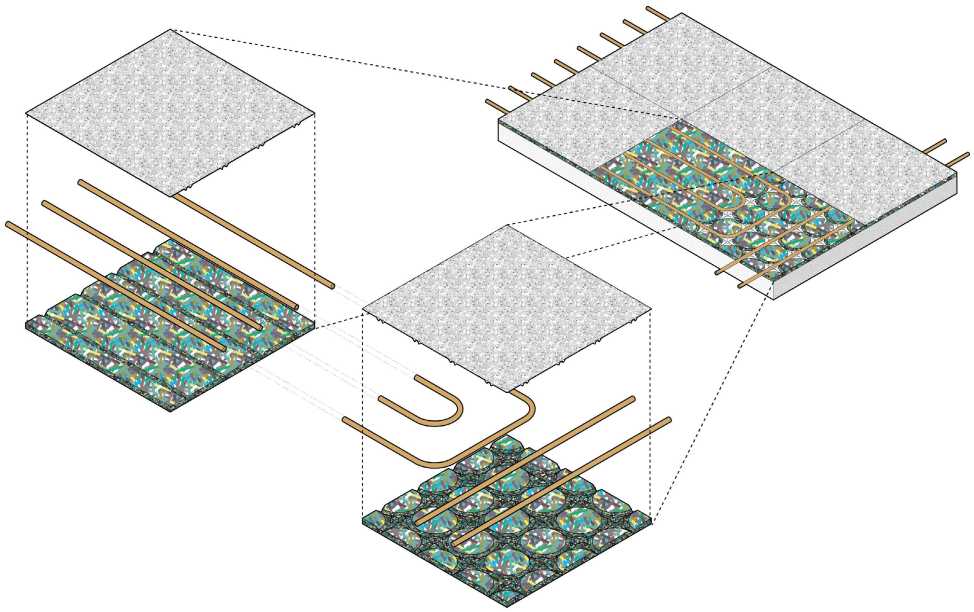
Underfloor heating is usually achieved by pumping hot water through tubes that are placed underneath the flooring. The tubes are placed (15 cm apart) on top of the structural flooring and usually covered with a layer of concrete. This concrete makes the surface flat so that finish floor can be laid on top. The concrete also distributes the heat from the tubes evenly across the floor. Although very effective, this type of underfloor heating is not demountable and therefore not circular. As a solution the tubes can be placed in foam tiles to make the surface level. However, the foam does not contribute to the heat distribution.

A tile system is designed using a foam layer of recycled unheated aluminium composite foil. This layer will function as a foam panel, holding standard underfloor heating tubes in their place and reducing acoustic vibrations when walking on the floor. Traditionally this layer is made out of expanded polystyrene (EPS) foam. The aluminium has a very high heat transfer coefficient making it an excellent material for a top layer. The cleaned aluminium is placed on top of the foam and this layer acts as a heat distributing element (figure 8.16). Especially for low temperature underfloor heating applications an even distribution of heat across the floor is important for a comfortable indoor climate.

The sectional drawing shows a tubular shaped protrusion that forms around the tubing. This increases the contact surface between the aluminium and the tube (8.17). The heat distribution is therefore more effective. Increasing the aluminium layer thickness will reduce the thermal resistance. A thicker layer of aluminium will increase the weight of the tile. If the foam panel acts as a stiff layer the overall thickness of the aluminium can be reduced. The effect of a thinner layer of aluminium is estimated in appendix G. When introduced to a 40°C water tube, an aluminium layer with 10 mm thickness will reach 38,0°C at the far end of the tile. A layer of only 1 mm thickness will reach 35,4°C furthest from the source. A tile with no aluminium layer and a finish floor placed directly on top will reach 18,1°C at the furthest end of the source. This shows the effectiveness of applying a layer of aluminium to the tile.

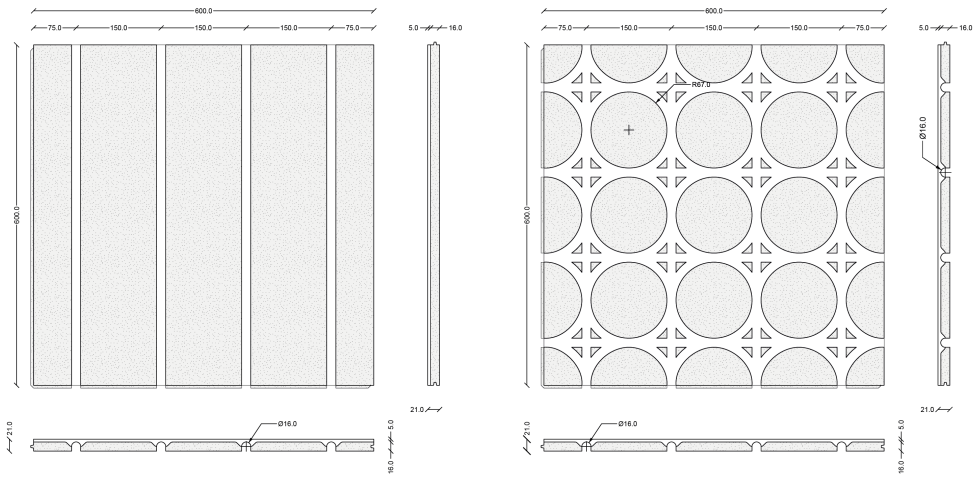
The underfloor heating tile is produced in two separate stages. First, a bottom polymer tile and a top aluminium tile are produced. These two panels must be separable during application to a building so that the tubing can be placed during installation (8.18).

Figure 8.16: *Underfloor heating tile*



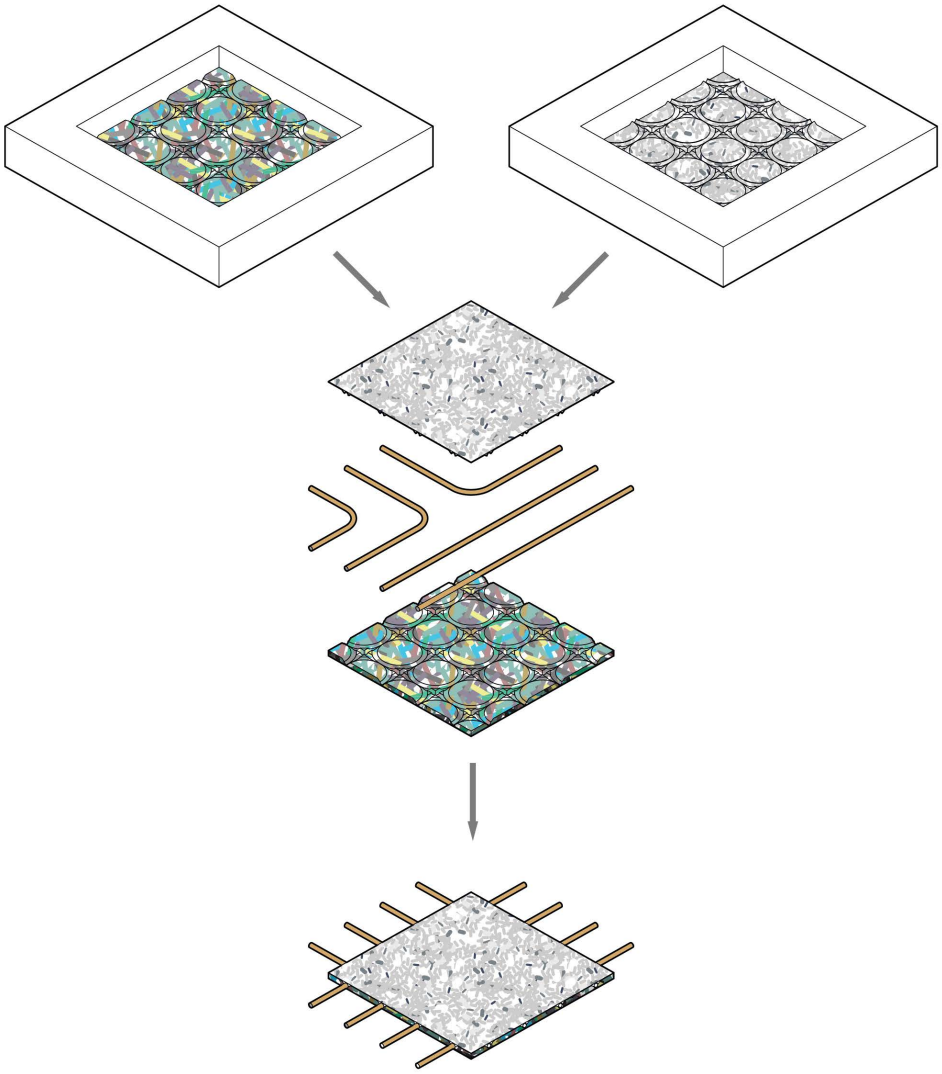
Note: An overview is shown of an indoor application as an underfloor heating tile.

Figure 8.17: *Technical drawing underfloor heating tile*



Note: The left drawing shows the underside of a 'straight' tile for straight applications. The right drawing shows the underside of a corner piece that can be used to make a turn in the tube. The hatched area represents a polymer layer. The white top layer represents the aluminium thermal conducting layer.

Figure 8.18: *Underfloor heating tile production*



Note: Different production techniques to integrate tubing in to the panel. On the left side a panel is produced, and the tubing is added after pressing. On the right side the tubing is placed in the powder and compressed together, this way the tubing is fused in the panel.

Processing, production & assembly

The different steps from material to product are schematically shown in figure 8.19. This figure is an overview of the steps described in the previous chapters and experiments.

Reversed workflow in material design

The used workflow - designing a material first and then searching for an application - is uncommon. A more typical approach would be an application and finding or designing a suitable material that meets the requirements.

The aluminium samples used for the bending test are shown to be much less strong than typical aluminium. Aluminium is typically used in structural applications because of its high strength to weight ratio. The sample material would underperform typical aluminium and therefore it makes no sense to replace structural applications. In particular, when using recycled material, material properties are often reduced compared to their original value. This phenomenon is described in chapter 3. In theory, more material can be used to achieve the same strength. This would however increase the weight of the element drastically, defeating its purpose.

When searching in the other direction, finding a logical and suitable application for a material is complicated. It requires a lot of knowledge about existing aluminium applications, current needs of the building environment and knowledge about the material you are designing with.

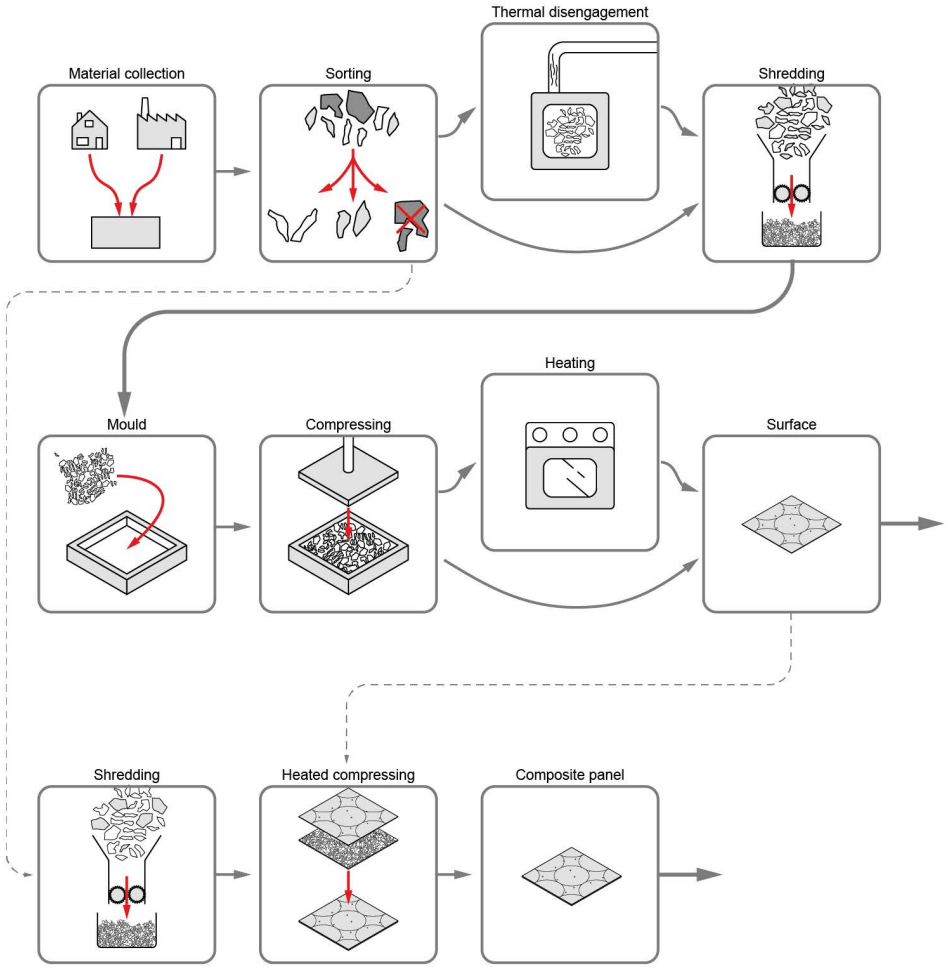
The constant balancing of material properties, expectations of the material and practical applications make the search of a suitable application extremely challenging.

Design tool

To simplify this task a design tool can be developed to help material scientists design a material and search for applications. Edupack is an excellent tool to search for material properties and compare materials. However, this software only describes existing materials and applications. A tool that can suggest new applications and ask for specific improvements of certain properties makes searching for an application and designing a material easier.

There are known companies and trade fairs that specialise in bringing designers and material scientists together. Closing the gap between material design and application. A supposed tool would give more direct input.

Figure 8.19: *Schematic overview of processing, production & assembly*



Note: The figure shows a step-by-step overview of the different steps used in the processing of the aluminium composite foil to produce the end-product.

9

Conclusion & Discussion

Research questions

The main research question *"How can un-recycled, contaminated, mixed metal waste be reprocessed into new materials for architectural applications?"* was answered in this thesis. The literature revealed that there are many un-recycled metal waste streams and many possibilities for reprocessing, let alone the many applications for this material. The subquestions that guided this thesis are discussed and concluded in the following sections.

"What is the current state of metal recycling in Europe, what difficulties are faced, and which waste streams stay un-recycled?"

The current state of recycling is complicated to assess and verifying recycling statistics is difficult. For the metal industry as a whole is a clear overview of waste streams available. However, there is a lack of information on specific types of metal-containing waste. Contaminated metal waste is not compatible with generic recycling methods. This metal waste contains contamination from metals that are normally presented as a combination. This leads to refining processes that are not compatible with this mixture resulting in losses of both or some of the metals in the mixture. These materials are therefore incinerated and landfilled. After researching potential, un-recycled materials, aluminium polymer composite foils were selected for further research.

Various techniques are used to produce these materials. They stay un-recycled due the strong bond between the polymer and the aluminium. The varying ratio of aluminium to polymer also makes recycling difficult.

"What are the parameters for processing this contaminated metal waste and how do they influence mechanical properties of the material?"

After doing initial research on aluminium composite foils and common recycling and production techniques powder metallurgy was taken as a starting point to research as a combination of a potential recycling and production techniques. A series of experiments were performed to explore this potential with a five-step workflow: granulate, press, heat. This led to a series of results with different parameters.

First, different granulation sizes were defined and pressed into desired a shape. More polymer in the foil would result in a sample that would not keep the desired shape. After heating an unstable result was created with little potential. Before heating the samples were somewhat rigid but also not very promising. The polymer interferes with the melting of the aluminium resulting in a very uncontrollable, porous sample results.

Heating the composite prior to granulation would result in a relatively clean aluminium that could be pressed into the desired shape. The fumes of the heated polymer can be collected a reused in petrochemical processes. The results of this technique were more promising and gave aluminium-like results. The recipe of thermally disengaged powder, compressed at 250 MPa and heated at 750°C for one hour gave the best results.

"What are potential architectural applications for these parameters and mechanical properties, and aesthetic qualities?"

The most promising recipe gave an average bending strength of 37 MPa, with as best result 50,4 MPa. This means that it

can be used, for example, to make facade panels. Aesthetically the surface of this material does present interesting results. Combining the non-heated results with the heated material as backing creates many attractive options both for indoor and outdoor applications.

However, finding an application for a newly designed material is complicated. A more common workflow would be having a design problem and look for a compatible material.

Aluminium is used in the architectural environment for its mechanical properties, commonly in lightweight applications. The recipe will result in only half of the flexural strength of normal aluminium. Therefore, it could theoretically be used to replace clean aluminium, but this would lead to more material use. Comparing it to other materials used for architectural application terracotta and plywood have comparable properties.

Research limitations

Granulation size

The experiments carried out showed that smaller particle sizes will give better results. For this research a coffee grinder was used to grind the aluminium shreds to the desired particle size. The smallest, average, particle size was estimated to be 1 mm. Smaller particle size where not researched but could hypothetically give better results. This could also potentially reduce the amount of pressure required to compress the material.

Oxygen limited environment

All samples showed oxidation on the surface. Samples compacted at lower pressures also showed oxidation in-between particles, potentially resulting in less bonding between the particles. To improve the performance of the proposed technique the effect of an oxygen limited environment could be researched. Reducing oxygen could result in less oxidation and therefore more bonding between particles.

Further research

Thermal disengagement

Thermal disengagement, to clean the aluminium composite foil, was carried out at 600°C for one hour. The literature describes that at this temperature most of the polymer would evaporate, leaving the smallest amount of carbon deposit. For further research would be interesting to investigate the effect of thermal disengagement at lower temperatures on the mechanical properties of the pressed aluminium samples.

Material recipe

Due to time constrains, only a handful of different parameters for the particle binding was tested. As a suggestion for further research, it may be useful to test increasing dwell times and temperatures.

Scalability

Compression is performed using a single cylinder press with one compression movement. As the surface area of an element is increased, the amount of force required from the press will increase linearly. For further research, different compression methods can be researched. For example, by using multiple cylinders or compressing only parts of the mould. Also, isostatic pressing could be researched to reduce the non-uniform compaction shown in the beam shaped samples.

Application guide

Software such as Edupack makes it easy to compare material properties. However, there is no software that suggests potential applications for newly designed materials. The ’cook and look’ approach of this thesis can lead to unexpected material results, making it complicated to find suitable applications for such a

material. The application section shows potential conceptual applications, but the material does not have a specific 'perfect' application.

Discussion

Assessing effectiveness

The research does not assess the cost or environmental impact of the proposed methods for reprocessing un-recycled metal waste. Several times the question was asked: ”How much does this process cost, both in energy, money and eco-footprint?” And if the costs were higher than the extraction of primary raw material, how would the criticality of the material, as defined by the European Union, be taken into account?

An attempt was made to assess the effectiveness of the method. However, after speaking to experts this assessment would be very speculative and there are no common methods for comparing criticality with cost.

Material collection

For this method of reprocessing, it is important to have an adequate supply of material. Collection of this material can be complicated because it is hard to separate them from other waste. Especially in the case of municipal waste contamination by other (food) waste can cause problems and would add complicity to the proposed method.

Depth of the research

Although the results are promising, it must be said that this is only a conceptual approach to reprocess un-recycled metal waste. The ’cook-and-look’ approach of this research gives quick results but also skips a lot of steps. Therefore, potential other approaches to reprocess un-recycled metal waste can have been overlooked. The thesis focuses only on aluminium polymer composites, leaving out a large amount of un-recycled metals.

10

Reflection

Position in the studio

This graduation thesis aligns closely with the faculty multi annual plan and the master track Building Technology. It addresses the topics of scarcity of resources, climate crisis and circularity in the built environment.

Research approach

Strength

By analysing waste streams and searching for materials not fitting in the current system a strong bases is created for a source material for further analysis. By searching conventional material handling methods a broad overview of the state of the art is retrieved. By selecting a certain approach specific knowledge is gained to research multiple possibilities for material treatment. The further research is a very analytical approach where there is a lot of control of different parameters.

Weakness

Due to the material not fitting in the current system there are little to no know effective techniques to recycle the material. Therefore, each step of the process must be researched and reviewed. This brings uncertainty and setbacks at unexpected moments.

Opportunities

Because the industry is relatively uninterested in these materials there is a lot of research freedom. From the perspective of sustainability every improvement compared to incineration is a benefit for the environment.

Threat

Material collection is shown to be difficult. The biggest question is where to retrieve relatively clean materials. The material used in this process is in theory more efficient when the aluminium content is the highest, this means that other parties are also interested in this material for recycling purposes. From a sustainability perspective it is very complicated to compare these processes.

Ethical considerations

The question what waste materials to include in this thesis and what to exclude was posed multiple times during the process. It is complicated to verify recycling effectiveness for waste material being exported outside of the EU. This does not mean that all material exported outside of the EU is recycled with low effectiveness. If recycling is done effectively, it is questionable at what kinds of worker circumstances this is done. Even though, these materials are excluded from this thesis to minimise the chance of cutting in effectively recycled waste streams.

Throughout this thesis, there was a constant debate about effectiveness of the proposed method. In theory, recycling is not effective if the process results in more emissions than would be produced by retrieving primary raw materials. The way in which material scarcity and criticality of a material interacts with this consideration is something that remains unanswered. Emission and costs are relatively straightforward to compare for different methods. Criticality is much more difficult to express in a number, which complicates comparing methods to each other.

Societal impact

The relevance of this thesis extends beyond the context of waste metals and creates a framework for researching other waste materials for architectural or other purposes. Creating awareness of the complexity of modern materials and minimal recycling solutions is crucial to reduce waste production. Recycling is not the answer to consumption and recyclability in theory is different than

recyclability in practice. Resource scarcity in the form of critical materials and climate crisis are both addressed.

Sustainable development

This thesis uses a resourceful approach to come up with solutions for critical material consumption and material waste. By proposing a feasible application for currently non-recyclable materials, the research can lead to improved practices in the built environment, and waste management sectors. By experimental testing of non-conservative recycling techniques new material will be created. By assessing the properties of the created material, the physical quality of the material can be shared among professional for potentially future application. However, compared to a final product, the tests conducted so far only scratch the surface. Further testing must be conducted to gain a more detailed overview of all the material's properties.

Scientific support

Scientifically, this work contributes to the broader field of materials science and environmental engineering by exploring new recycling methods and correlating material processing to properties. It should encourages further investigation into material properties, the technologies involved in recycling, and the potential environmental benefits of recycling complex or low-value materials.

However, during this thesis I have come across a number of people and institutions that seem to have doubts about the research approach and the effectiveness of conducting research in this field. They had doubts mainly about the approach of using non-conservative reprocessing techniques, as well as about the overall yield and impact of the problem that is addressed. The metal industry is stubborn and does not seem to be very open for new concepts and ideas. This may be partly due to the way the metal industry is formed, as described in the literature.

Impact

Waste is everywhere and therefore also in the built environment. The challenge in the built environment is the consumption of materials and the scale at which this is done. Therefore, small changes and developments in material science can have mayor impact on the footprint of the building industry. Although development of more sustainable materials and more effective and innovative techniques for recycling and material handling are developed it is very clear that specific materials are used for specific applications. Therefore, changing the material and its properties will unleash a cascade of changes in a building system. This will take a lot of time and effort for the industry to adapt.

References

Al Mahmood, A., Hossain, R., & Sahajwalla, V. (2019). Microrecycling of the metal–polymer-laminated packaging materials via thermal disengagement technology. *SN Applied Sciences*, *1*(9). https://doi.org/10.1007/s42452-019-1099-7

Al Mahmood, A., Hossain, R., & Sahajwalla, V. (2020). Investigation of the effect of laminated polymers in the metallic packaging materials on the recycling of aluminum by thermal disengagement technology (TDT). *Journal of Cleaner Production*, *274*. https://doi.org/10.1016/j.jclepro.2020.122541

Alancaster. (2024). Bauxite Mining. *Encyclopedia of Arkansas*. https://encyclopediaofarkansas.net/media/bauxite-mining-21722/

Aluminium, I. (2022, May). Recyclable - the aluminium story. https://thealuminiumstory.com/transport/recyclable/

American Welding Society. (2020). *Standard Welding Terms and Definitions* (13th ed.).

ANSYS, Inc. (2023). *Ansys granta edupack* (Version 2023 edition) [Computer software]. https://www.ansys.com/products/materials/granta-edupack

Bartczak, Z., Argon, A. S., Cohen, R. E., & Weinberg, M. (1998). *Toughness mechanism in semi-crystalline polymer blends: II. High-density polyethylene toughened with calcium carbonate filler particles* (tech. rep.).

Björkman, B., & Samuelsson, C. (2014, May). Recycling of Steel. In *Handbook of recycling: State-of-the-art for practitioners, analysts, and scientists* (pp. 65–83). Elsevier Inc. https://doi.org/10.1016/B978-0-12-396459-5.00006-4

Buschow, K. H. J. (2001a). Machining and machinability. In *Encyclopedia of materials: Science and technology* (pp. 4683–4692, Vol. 5). Elsevier.

Buschow, K. H. J. (2001b). MIM. In *Encylopedia of materials: Science and technology* (pp. 5439–5442, Vol. 6). Elsevier.

Castro, M. B., Remmerswaal, J. A., Reuter, M. A., & Boin, U. J. (2004). A thermodynamic approach to the compatibility of materials combinations for recycling. *Resources, Conservation and Recycling*, *43*(1), 1–19. https://doi.org/10.1016/j.resconrec.2004.04.011

Cervantes-Reyes, A., Núñez-Pineda, A., Barrera-Díaz, C., Varela-Guerrero, V., Martínez-Barrera, G., & Cuevas-Yañez, E. (2015). Solvent effect in the polyethylene recovery from multilayer postconsumer aseptic packaging. *Waste Management*, *38*(1), 61–64. https://doi.org/10.1016/j.wasman.2015.01.034

Coker, E. N. (2013). *The oxidation of aluminum at high temperature studied by Thermogravimetric Analysis and Differential Scanning Calorimetry* (tech. rep.). http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

Damgaard, A., Larsen, A. W., & Christensen, T. H. (2009).

Recycling of metals: accounting of greenhouse gases and global warming contributions. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *27*(8), 773–780. https://doi.org/10.1177/0734242X09346838

European Commission and Directorate-General for Internal Market Industry Entrepreneurship and SMEs, Grohol, M., & Veeh, C. (2023). *Study on the critical raw materials for the EU 2023 – Final report*. Publications Office of the European Union. https://doi.org/doi/10.2873/725585

Eurostat. (2023a). Energy statistics - quantities, annual data. https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_s__custom_14872067/default/table?lang=en

Eurostat. (2023b). Greenhouse gas emissions by source sector. https://ec.europa.eu/eurostat/databrowser/view/env_air_gge/default/table?lang=en

Eurostat. (2023c). Management of waste by waste management operations and type of material - Sankey diagram data. https://ec.europa.eu/eurostat/cache/sankey/circular_economy/sankey.html?geos=EU27_2020&unit=THS_T&materials=TOTAL&material=TOTAL&highlight=0&nodeDisagg=0101100100&flowDisagg=false&language=EN

Graedel, T. E., Allwood, J., Birat, J. P., Buchert, M., Hagelüken, C., Reck, B. K., Sibley, S. F., & Sonnemann, G. (2011). What do we know about metal recycling rates? *Journal of Industrial Ecology*, *15*(3), 355–366. https://doi.org/10.1111/j.1530-9290.2011.00342.x

Gura, D. (2010, October). Toxic Red Sludge Spill From Hungarian Aluminum Plant 'An Ecological Disaster'. https://www.npr.org/sections/thetwo-way/2010/10/05/130351938/red-sludge-from-hungarian-aluminum-plant-spill-an-ecological-disaster

Hassan, A., & Alnaser, I. A. (2024, February). A Review of Different Manufacturing Methods of Metallic Foams. https://doi.org/10.1021/acsomega.3c08613

Hebel, D. E., Wisniewska, M. H., & Heisel, F. (2014, December). *Building from Waste*. DE GRUYTER. https://doi.org/10.1515/9783038213758

Kerry, J. (2012). *Aluminium foil packaging* (tech. rep.).

Khan, W. S., Asmatulu, E., Uddin, M. N., & Asmatulu, R. (2022). Recycling and reusing of metals and alloys. In *Recycling and reusing of engineering materials* (pp. 163–179). Elsevier. https://doi.org/10.1016/b978-0-12-822461-8.00006-1

Krishnan, S., Zulkapli, N. S., Kamyab, H., Taib, S. M., Din, M. F. B. M., Majid, Z. A., Chaiprapat, S., Kenzo, I., Ichikawa, Y., Nasrullah, M., Chelliapan, S., & Othman, N. (2021, May). Current technologies for recovery of metals from industrial wastes: An overview. https://doi.org/10.1016/j.eti.2021.101525

Lancaster, J. F. (1980). Brazing, soldering and adhesive bonding. In *Metallurgy of welding* (pp. 87–109). Springer Netherlands. https://doi.org/10.1007/978-94-010-9506-8{_}6

Lin, C., Paengsri, P., & Yang, Y. (2023). Impact of China's National Sword Policy on waste import:A difference-in-differences approach. *Economic Analysis and Policy*, *78*, 887–903. https://doi.org/10.1016/j.eap.2023.04.033

Material properties. (2025). Material District - New material for Architecture, Interior. materialdistrict.com

Mendoza-Duarte, J. M., Estrada-Guel, I., Garcia-Herrera, J. E., Perez-Bustamante, R., Arcos-Gutiérrez, H., Martinez-García, A., Sánchez, X. A., Garay-Reyes, C. G., Carreño-Gallardo, C., & Martínez-Sánchez, R. (2024). Aluminum carbide formation in Al-graphite composites: In situ study and effects of processing variables and sintering method. *Materials Today Communications*, *38*. https://doi.org/10.1016/j.mtcomm.2024.108396

Morris, B. A. (2017). Commonly Used Resins and Substrates in Flexible Packaging. In *The science and technology of flexible packaging* (pp. 69–119). Elsevier. https://doi.org/10.1016/b978-0-323-24273-8.00004-6

Nayak, K. C., Rane, K. K., Date, P. P., & Srivatsan, T. S. (2022). Synthesis of an Aluminum Alloy Metal Matrix Composite Using Powder Metallurgy: Role of Sintering Parameters. *Applied Sciences (Switzerland)*, *12*(17). https://doi.org/10.3390/app12178843

Onwudili, J. A., Insura, N., & Williams, P. T. (2009). Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: Effects of temperature and residence time. *Journal of Analytical and Applied Pyrolysis*, *86*(2), 293–303. https://doi.org/10.1016/j.jaap.2009.07.008

Papantoniou, I. G., Markopoulos, A. P., Pantelis, D. I., & Manolakos, D. E. (2018). Application of aluminium flakes in fabrication of open-cell aluminium foams by space holder method. *Materials*, *11*(8). https://doi.org/10.3390/ma11081420

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017, January). *CIRCULAR ECONOMY: MEASURING INNOVATION IN THE PRODUCT CHAIN* (tech. rep.). https://www.researchgate.net/publication/319314335

Regulation (EU) 2024/1252 Of the european parliament and of the council. (2024). *Official Journal of the European Union*. http://data.europa.eu/eli/reg/2024/1252/oj

Reuter, M. A., Boin, U. M. J., van Schaik, A., & Verhoef, E. V. (2003). *Pyrometallurgy: The key to sustainable use of materials*. South African Institute of Mining; Metallurgy.

Reuter, M. A., Heiskanen, K., Boin, U., Van Schaik, A., Verhoef, B., Yang, Y., & Georgalli, G. (2005). *The Metrics of Material and Metal Ecology, Harmonizing the resource, technology and environmental cycles* (tech. rep.). https://www.researchgate.net/publication/264942361

Riedewald, F., Wilson, E., Patel, Y., Vogt, D., Povey, I., Barton, K., Lewis, L., Caris, T., Santos, S., O'Mahoney, M., & Sousa-Gallagher, M. (2022). Recycling of aluminium laminated pouches and Tetra Pak cartons by molten metal pyrolysis – Pilot-scale experiments and economic analysis. *Waste Management*, *138*, 172–179. https://doi.org/10.1016/j.wasman.2021.11.049

Rojas, C. (2025, June). CaixaForum Sevilla / Vázquez Consuegra. https://www.archdaily.com/882996/caixaforum-sevilla-vazquez-consuegra

Schneider, D. R., & Ragossnig, A. M. (2015, August). Recycling and incineration, contradiction or

coexistence? https://doi.org/10.1177/0734242X15593421

Smil, V. (2016). Materials in Modern Iron and Steel Production. In *Still the iron age* (pp. 115–138). Elsevier. https://doi.org/10.1016/b978-0-12-804233-5.00006-3

Somsuk, N., Wessapan, T., Teekasap, S., Somsuk, *. N., Wessapan, T., Sutthisong, S., Hussaro, K., & Teekasap, S. (2009). *Development of a Heat Exchanger Used With Pyrolysis Oven in Wood Vinegar Production* (tech. rep.). https://www.researchgate.net/publication/284332597

Suseno, A. (2015, October). Mining of sulfur from a deposit at the edge of Ijen's crater lake, Indonesia. https://en.wikipedia.org/wiki/Mining#/media/File:Sulphur_Mining_at_Kawah_Ijen_3.jpg

Tabereaux, A. T., & Peterson, R. D. (2014). Aluminum Production. In *Treatise on process metallurgy* (pp. 839–917, Vol. 3). Elsevier Ltd. https://doi.org/10.1016/B978-0-08-096988-6.00023-7

Themelis, N. J. (2018). Recovery of Materials and Energy from Urban Waste. In *Encyclopedia of sustainability science and technology* (Second Edition). Springer New York. https://doi.org/10.1007/978-1-4939-2493-6{_}394-4

Tuncuk, A., Stazi, V., Akcil, A., Yazici, E. Y., & Deveci, H. (2012). Aqueous metal recovery techniques from e-scrap: Hydrometallurgy in recycling. *Minerals Engineering*, *25*(1), 28–37. https://doi.org/10.1016/j.mineng.2011.09.019

Van Langen, S. K., Vassillo, C., Ghisellini, P., Restaino, D., Passaro, R., & Ulgiati, S. (2021). Promoting circular economy transition: A study about perceptions and awareness by different stakeholders groups. *Journal of Cleaner Production*, *316*, 128166. https://doi.org/10.1016/j.jclepro.2021.128166

Van Schaik, A., & Reuter, M. A. (2004). The time-varying factors influencing the recycling rate of products. *Resources, Conservation and Recycling*, *40*(4), 301–328. https://doi.org/10.1016/S0921-3449(03)00074-0

Van Schaik, A., Reuter, M. A., Boin, U. M. J., & Dalmijn, W. L. (2002). *Dynamic modelling and optimisation of the resource cycle of passenger vehicles q* (tech. rep.). www.elsevier.com/locate/mineng

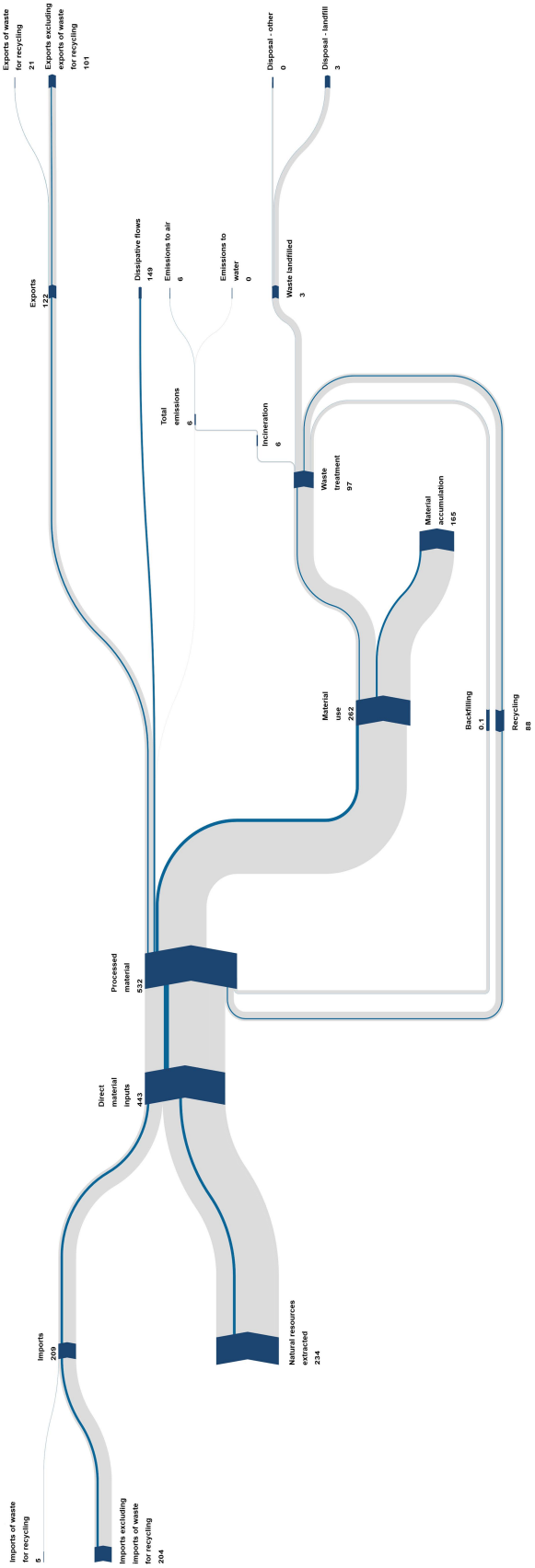
Verhoef, E., Dijkema, G. P. J., & Reuter, M. A. (2000, September). *The complexity of material cycle simulation and design co-incineration* (tech. rep.). Melbourne, Australia. https://www.researchgate.net/publication/276597240

Worldsteel. (2021, May). *Scrap use in the steel industry Fact sheet* (tech. rep.). https://worldsteel.org/wp-content/uploads/Fact-sheet-on-scrap_2021.pdf

ZwickRoell materials testing. (2025). https://www.zwickroell.com/nl/

A

Sankey Diagram metal ore flow Europe


Exports of waste for recycling 21
Exports excluding exports of waste for recycling 101
Disposal - other 0
Disposal - landfill 3
Exports 122
Dissipative flows 149
Emissions to air 6
Emissions to water 0
Waste landfilled 3
Total emissions 6
Incineration 6
Waste treatment 97
Material accumulation 165
Material use 262
Backfilling 0.1
Recycling 88
Processed material 532
Direct material inputs 443
Imports 209
Natural resources extracted 234
Imports of waste for recycling 5
Imports excluding imports of waste for recycling 204

B

Fourier results

C

XRD and XRF analysis

X-RAY FACILITIES GROUP

Dr. Amarante Böttger

Dhr. Ruud Hendrikx
Drs. Richard Huizenga

Delft University of Technology, Faculty of ME
Department of Materials Science and Engineering
Mekelweg 2, NL-2628 CD Delft, the Netherlands, phone +31(0)152789459

XRD identification of Aluminium foams

Author	:	Ruud Hendrikx
Date	:	10 mar 2025
Researcher	:	Hidde van Nieuwenhoven, BK
Research question	:	Phase identification

Samples

"Recycling foil Al-polyethylene composites to make Al foams.
After a number of tests in a slow oven and in air, a relatively large amount of Aluminium oxide is probably formed, which makes the Aluminium difficult to sinter."

Specimens

Sample material was deposited on a Si510 zero-background wafer.

Experimental

Instrument: Bruker D8 Advance diffractometer Bragg-Brentano geometry and Lynxeye-XE-T position sensitive detector. Cu Kα radiation. Divergence slit V12, scatter screen height 5 mm, 45 kV 40 mA. No sample spinning. Detector settings: "high resolution".

Measurements

Coupled θ -2θ scan 10° - 110°, step size 0.03 ° 2θ, counting time per step 1 s.

Data evaluation

Bruker software DiffracSuite.EVA vs 7.3.

identification

Figures 1 to 3 show the measured XRD patterns, after background subtraction and small displacement correction. For better display of the small peaks, the intensity scales are square root. The colored sticks give the peak positions and intensities of the possibly present crystalline phases, using the ICDD pdf5 and COD databases.
The identified compounds are listed in table 1. Aluminium-oxides were not found. Not all small peaks could be identified.

sample	*compound*	
S2_650-700-750C	Aluminium	Al
	Lime	CaO
	Calcite	CaCO3
S2_CF-CR_750C	Aluminium	Al
	Lime	CaO
	Calcite	CaCO3
S4_650-700-750C	Aluminium	Al
	Silicon	Si

Table 1.

If the analysis is a significant part of a publication, a co-authorship is preferred.

In any case, it is useful to involve us in the preparation of any presentation to ensure optimum and correct use of the analysis results!

Whenever used in a publication, an acknowledgement will be appreciated, e.g.: "personX at the Department of Materials Science and Engineering of the Delft University of Technology is acknowledged for the X-ray analysis".

Sample "S2_650-700-750C"

sample "S2_CF-CR_750C"

Sample "S4_650-700-750C"

Figure 1 video pictures of the three specimens (from left to right is 8 mm)

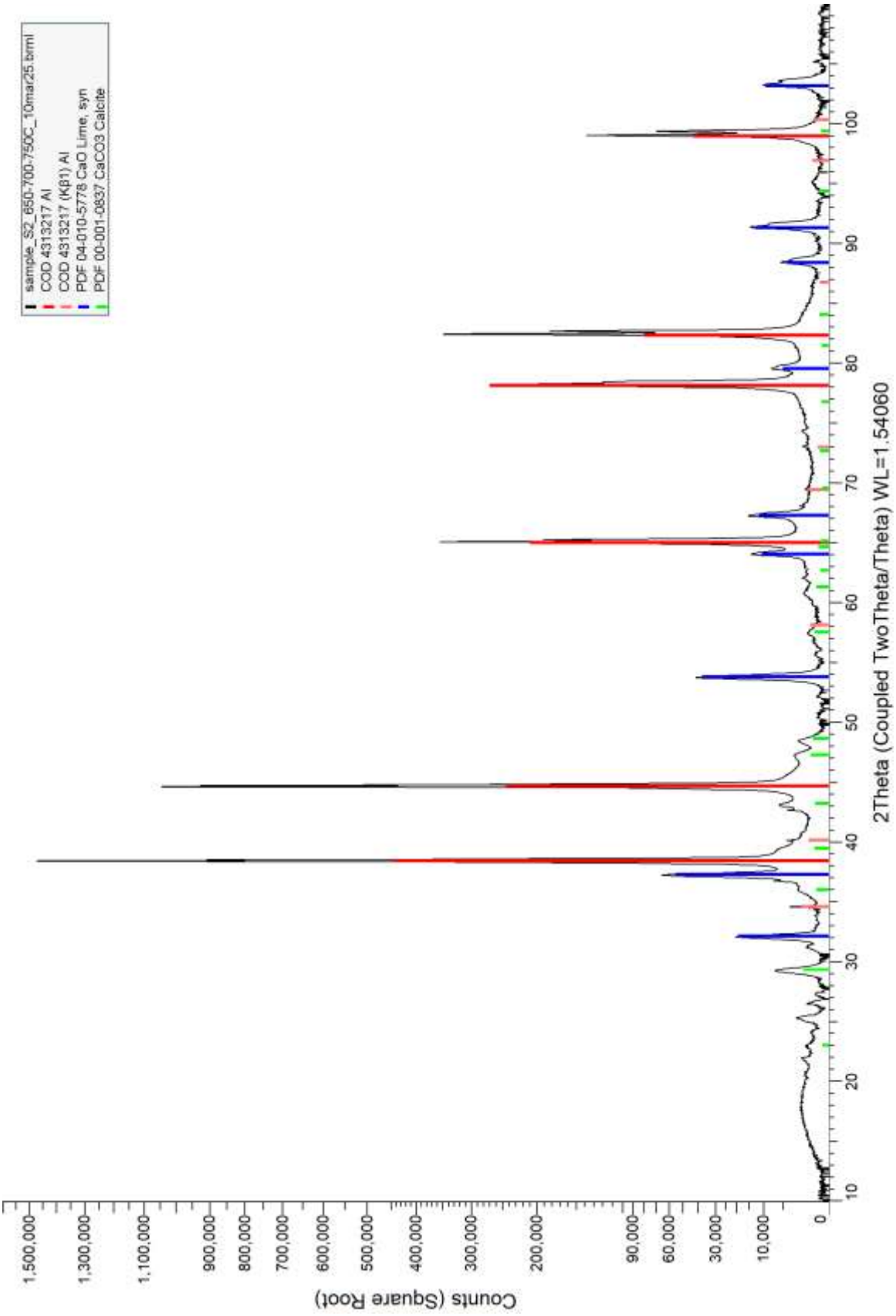


Figure 2 XRD pattern sample " S2_650-700-750 ºC ", the intensity scale is square root

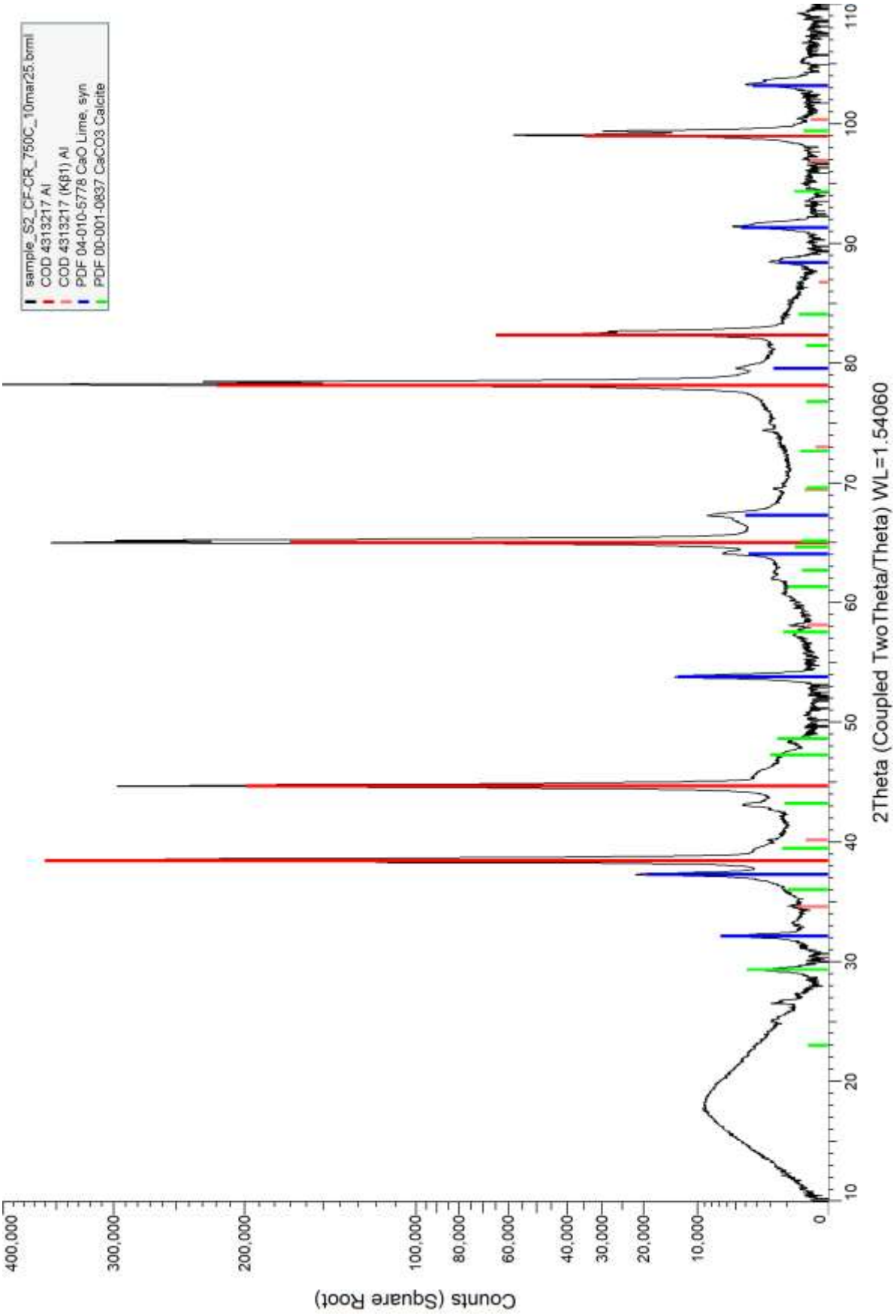


Figure 3 XRD pattern sample "S2_CF-CR_750ºC", the intensity scale is square root

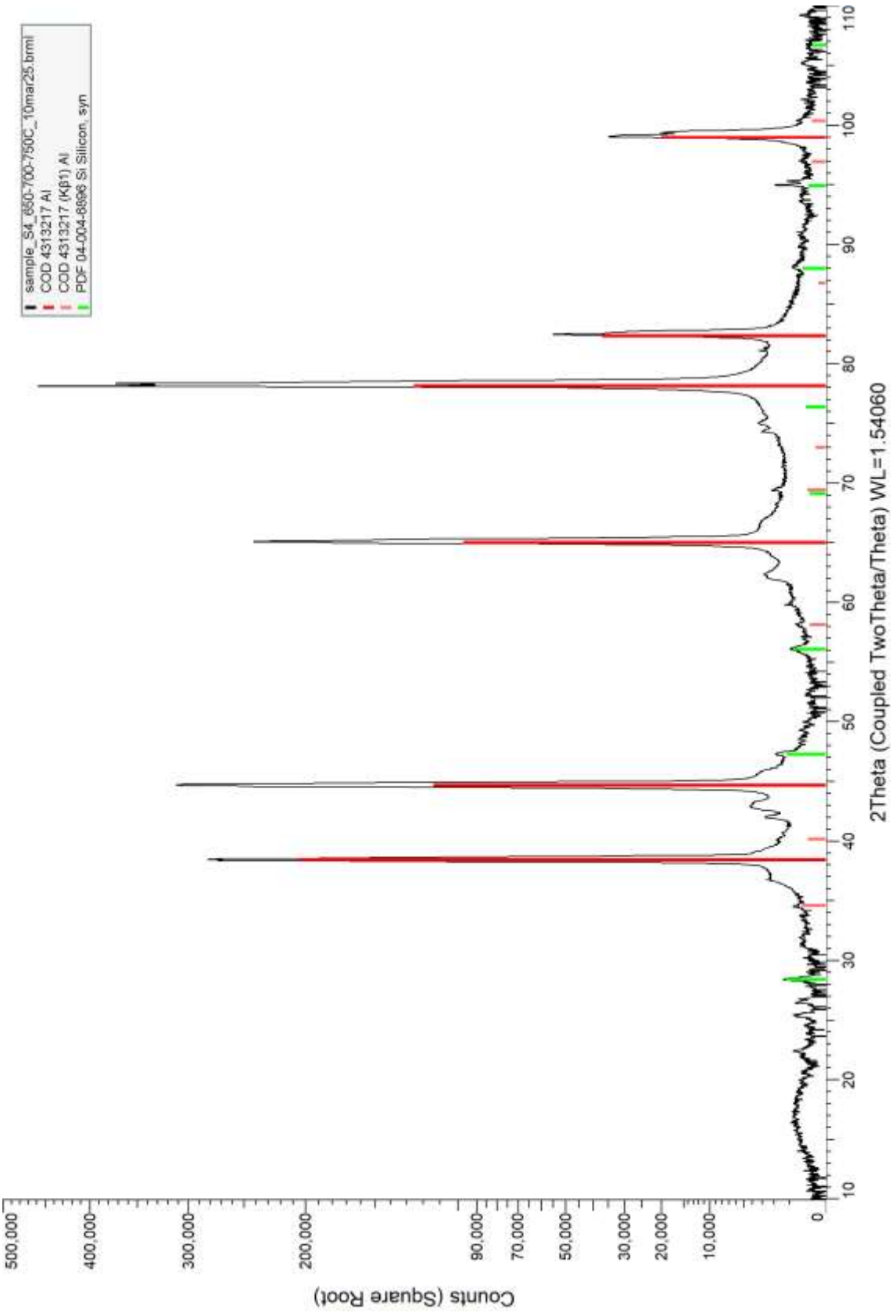


Figure 4 XRD pattern sample " S4_650-700-750°C ", the intensity scale is square root

Materials Science and Engineering
TUDelft, Faculty of 3mE
Mekelweg 2
2628 CD Delft, The Netherlands
Tel:015-2789459
Email: R.W.A.Hendrikx@tudelft.nl

X- ray diffraction facilities

Experimental conditions:

For XRF analysis the measurements were performed with a Panalytical Axios Max WD-XRF spectrometer and data evaluation was done with SuperQ5.0i/Omnian software. 18/12/2015 09:37:03

3/24/2025 3:08:00 PM

PANalytical

Quantification of sample Hidde van Nieuwenhoven, "S7 0.125 seef", 24mar25

Sum before normalization: 65.3 wt%

Normalised to: 100.0 wt%

Sample type: Loose powder

Correction applied for medium: Yes

Correction applied for film: Yes

Results database: omnian 4kw 27he

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Si	48.007	0.1
2	Al	32.988	0.1
3	Mg	13.878	0.1
4	Fe	2.789	0.05
5	Ca	1.491	0.06
6	Zn	0.224	0.01
7	Cu	0.141	0.01
8	P	0.128	0.01
9	S	0.12	0.01
10	K	0.06	0.007
11	Ti	0.058	0.007
12	Pb	0.058	0.007
13	Mn	0.042	0.006
14	Ni	0.016	0.004

3/24/2025 3:10:46 PM

PANalytical

Quantification of sample Hidde van Nieuwenhoven, "S7 P.CR 750C seef", 24mar25

Sum before normalization: 54.0 wt%

Normalised to: 100.0 wt%

Sample type: Loose powder

Correction applied for medium: Yes

Correction applied for film: Yes

Results database: omnian 4kw 27he

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	84.037	0.1
2	Si	11.05	0.09
3	Fe	2.522	0.05
4	Mg	1.967	0.04
5	Ca	0.142	0.02
6	Ti	0.048	0.007
7	Zn	0.044	0.006
8	P	0.039	0.006
9	Cu	0.034	0.006
10	Mn	0.031	0.005
11	S	0.025	0.005
12	Pb	0.018	0.004
13	V	0.017	0.004
14	Ni	0.015	0.004
15	K	0.011	0.003

Materials Science and Engineering
TUDelft, Faculty of 3mE
Mekelweg 2
2628 CD Delft, The Netherlands
Tel:015-2789459
Email: R.W.A.Hendrikx@tudelft.nl

X- ray diffraction facilities

Experimental conditions:

For XRF analysis the measurements were performed with a Panalytical Axios Max WD-XRF spectrometer and data evaluation was done with SuperQ5.0i/Omnian software. 18/12/2015 09:37:03

5/28/2025 11:11:41 AM

PANalytical

Quantification of sample H. v Nieuwenhoven, "s5" 28may25

Sum before normalization: 28.6 wt%

Normalised to: 100.0 wt%

Sample type: Loose powder

Correction applied for medium: Yes

Correction applied for film: Yes

Results database: omnian 4kw 27he

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	72.072	0.1
2	Si	21.507	0.1
3	Fe	2.801	0.05
4	Mg	2.696	0.05
5	Cl	0.254	0.02
6	Ca	0.225	0.01
7	Zn	0.09	0.009
8	P	0.082	0.009
9	Ti	0.079	0.008
10	Mn	0.055	0.007
11	S	0.038	0.006
12	Cr	0.037	0.006
13	Cu	0.036	0.006
14	Ni	0.029	0.005

5/28/2025 11:14:33 AM

PANalytical

Quantification of sample H. v Nieuwenhoven, "s5 p" 28may25

Sum before normalization: 57.8 wt%

Normalised to: 100.0 wt%

Sample type: Loose powder

Correction applied for medium: Yes

Correction applied for film: Yes

Results database: omnian 4kw 27he

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	91.519	0.1
2	Si	5.459	0.07
3	Fe	1.554	0.04
4	Mg	1.239	0.03
5	Ti	0.048	0.007
6	Ca	0.034	0.006
7	Mn	0.032	0.005
8	P	0.026	0.005
9	V	0.025	0.005
10	Zn	0.022	0.004
11	S	0.017	0.004
12	Cu	0.014	0.004
13	Ni	0.012	0.003

5/28/2025 11:22:03 AM

PANalytical

Quantification of sample H. v Nieuwenhoven, "s6" 28may25

Sum before normalization: 34.3 wt%

Normalised to: 100.0 wt%

Sample type: Loose powder

Correction applied for medium: Yes

Correction applied for film: Yes

Results database: omnian 4kw 27he

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	69.971	0.1
2	Si	23.484	0.1
3	Mg	2.7	0.05
4	Fe	2.367	0.05
5	Cl	0.824	0.03
6	Ca	0.231	0.03
7	P	0.116	0.01
8	Zn	0.088	0.009
9	Ti	0.074	0.008
10	Mn	0.042	0.006
11	S	0.033	0.005
12	Cu	0.027	0.005
13	Ni	0.024	0.005
14	V	0.019	0.004

5/28/2025 11:24:01 AM

PANalytical

Quantification of sample H. v Nieuwenhoven, "s6 p" 28may25

Sum before normalization: 58.7 wt%

Normalised to: 100.0 wt%

Sample type: Loose powder

Correction applied for medium: Yes

Correction applied for film: Yes

Results database: omnian 4kw 27he

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	92.253	0.1
2	Si	4.887	0.06
3	Fe	1.475	0.04
4	Mg	1.176	0.03
5	Ti	0.06	0.007
6	Ca	0.025	0.005
7	V	0.024	0.005
8	P	0.024	0.005
9	Zn	0.023	0.005
10	Cu	0.016	0.004
11	Mn	0.015	0.004
12	S	0.013	0.003
13	Ni	0.01	0.003

5/28/2025 9:18:01 AM

PANalytical

Quantification of sample H. v Nieuwenhoven, "s7" 28may25

Sum before normalization: 41.4 wt%

Normalised to: 100.0 wt%

Sample type: Loose powder

Correction applied for medium: Yes

Correction applied for film: Yes

Results database: omnian 4kw 27he

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	76.805	0.1
2	Si	16.992	0.1
3	Fe	2.13	0.04
4	Mg	2.018	0.04
5	Cl	0.795	0.03
6	P	0.621	0.07
7	Ca	0.313	0.04
8	Zn	0.066	0.008
9	S	0.064	0.008
10	Ti	0.062	0.007
11	Cu	0.047	0.007
12	Mn	0.04	0.006
13	K	0.033	0.005
14	Ni	0.013	0.003
15	Zr	0.003	0.002

5/28/2025 9:14:43 AM

PANalytical

Quantification of sample H. v Nieuwenhoven, "s7 p" 28may25

Sum before normalization: 58.2 wt%

Normalised to: 100.0 wt%

Sample type: Loose powder

Correction applied for medium: Yes

Correction applied for film: Yes

Results database: omnian 4kw 27he

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Al	89.863	0.1
2	Si	6.817	0.08
3	Fe	1.628	0.04
4	Mg	1.458	0.04
5	Ti	0.044	0.006
6	Ca	0.037	0.006
7	V	0.028	0.005
8	Zn	0.025	0.005
9	P	0.024	0.005
10	Mn	0.021	0.004
11	S	0.014	0.003
12	K	0.012	0.003
13	Ni	0.012	0.003
14	Cu	0.008	0.003
15	Cr	0.007	0.003
16	Zr	0.002	0.001

Use of our XRD or XRF analysis:
In a publication: 'PersonX at the Department of Materials Science and Engineering of the Delft University of Technology is acknowledged for the X-ray analysis. If it is an important part of the publication: a co-authorship is preferred. It is useful to involve us in the preparation of any presentation!

D

Sample overview

Virgin samples

Fired samples

Untreated samples

Granulation: Powder (<2mm) | Compaction: 250 MPa | Temperature: 20

S2 S3 S4 S5 S6 S7

Granulation: Powder (<2mm) | Compaction: 250 MPa | Temperature: 110

S1 S2 S3 S4

Granulation: Flakes (2-20mm) | Compaction: 250 MPa | Temperature: 20

S1 S2 S3 S5 S6 S7

Granulation: Flakes (2-20mm) | Compaction: 250 MPa | Temperature: 110

S1 S2 S3

Granulation: String (<50mm) | Compaction: 250 MPa | Temperature: 20

S1 S2 S5 S6 S7

Granulation: String (<50mm) | Compaction: 250 MPa | Temperature: 110

S1 S2

Cleaned samples

Granulation: Powder (2mm) | Compaction: variable | Temperature: 20

S5 S5 S5

Granulation: Powder (2mm) | Compaction: variable | Temperature: 20

S6 S6 S6

Granulation: Powder (2mm) | Compaction: variable | Temperature: 20

S7 S7 S7

Granulation: Powder (2mm) | Compaction: 250 MPa | Temperature: 20

S2 S5 S6 S7

Contamination

Granulation: Strings (0-20mm) | Compaction: 250 MPa | Temperature: 20

50% 40% 30% 20% 10% 0%

Surfaces

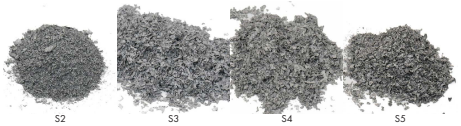
Granulation: Powder (<2mm) | Compaction: 250 MPa | Temperature: 20

Untreated Untreated textured Polished Semi polished

Composites

Granulation: String (<50mm) | Compaction: | Temperature:

S1 S7 S3 S4 S1 firm S1 fluffy



S2 S3 S4 S5

S1 S2 S3 S4

S1 S2 S3 S5

S1 S2

50 MPa, 700 100 MPa, 700 250 MPa, 700 50 MPa, 750 100 MPa, 750 250 MPa, 750

50 MPa, 700 100 MPa, 700 250 MPa, 700 50 MPa, 750 100 MPa, 750 250 MPa, 750

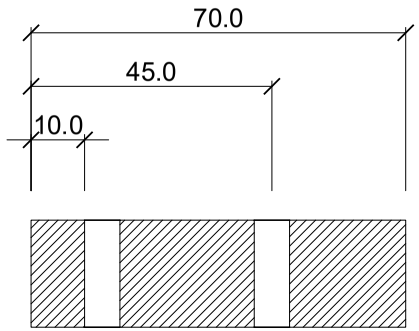
50 MPa, 700 100 MPa, 700 250 MPa, 700 50 MPa, 750 100 MPa, 750 250 MPa, 750

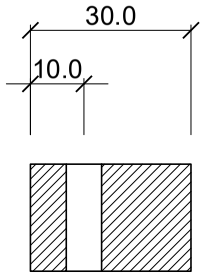
900 750 750 750

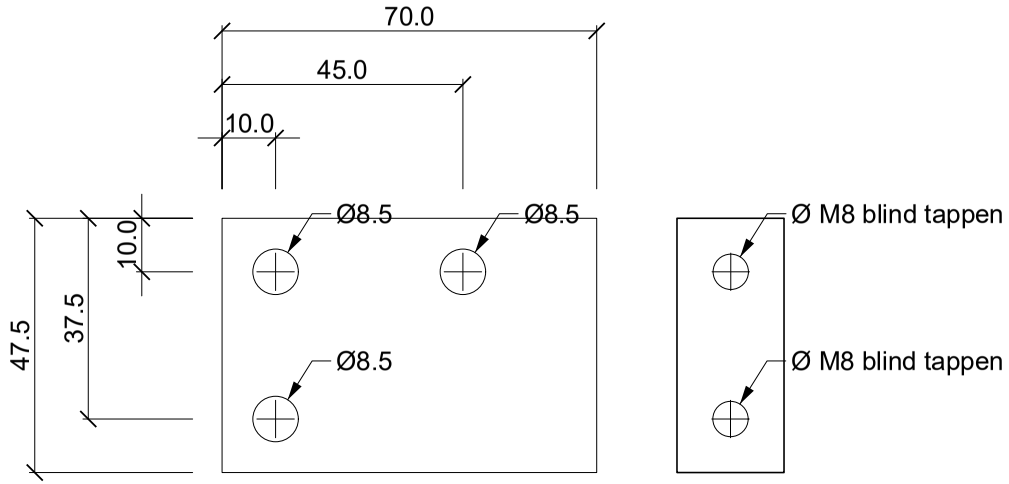
50% 40% 30% 20% 10% 0%

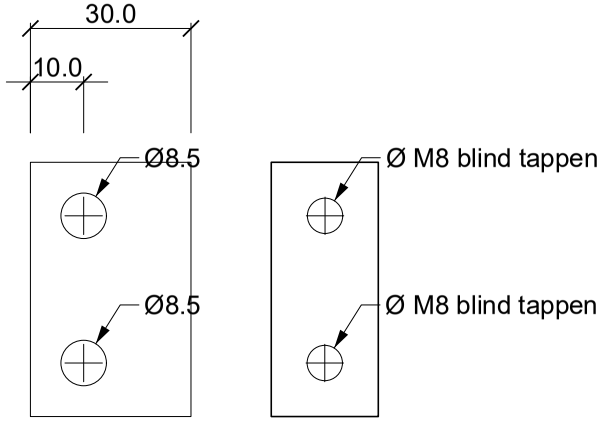
E

Moulds

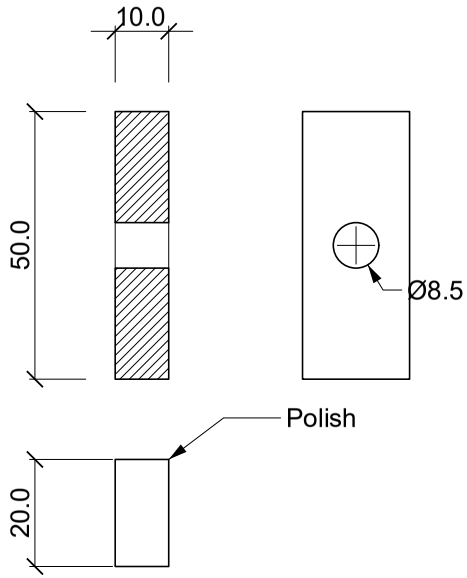


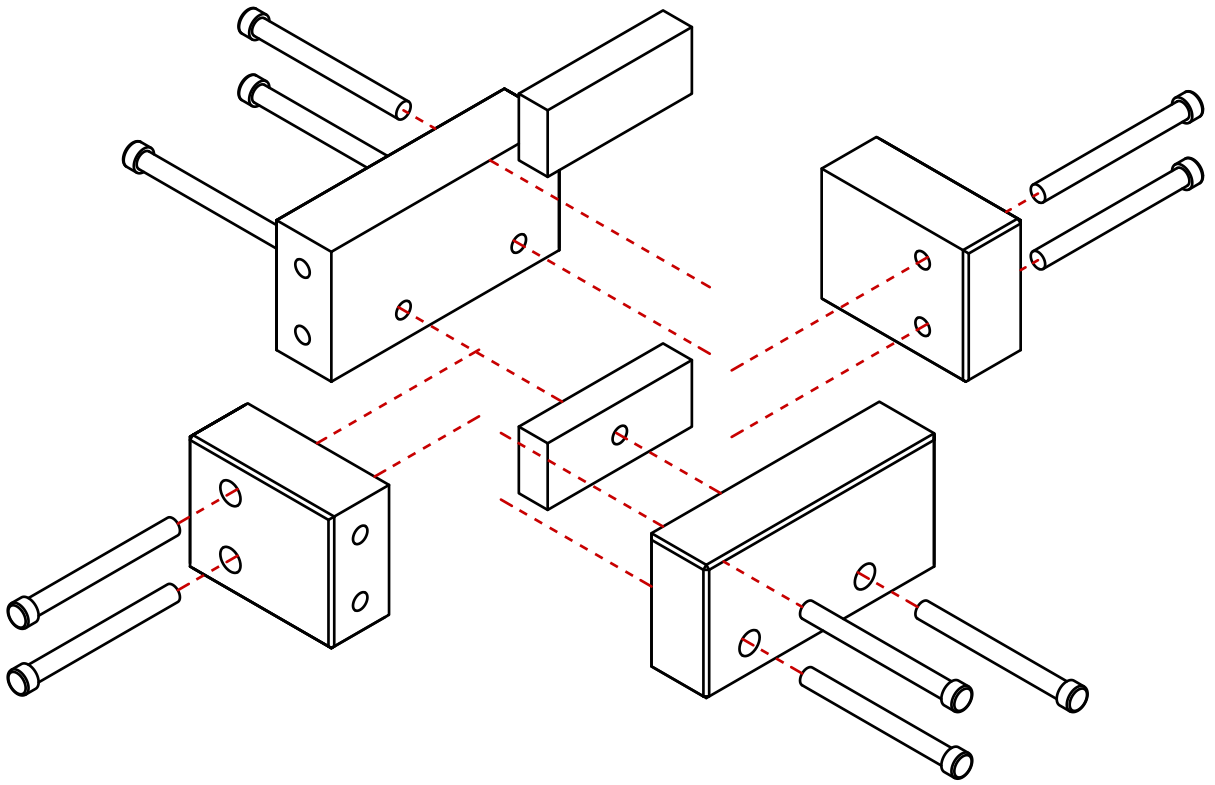






Project: Mould	
####	####
1:1	
Content: Sides	Size A3
Date: 4/22/2025	





Project: Mould	
####	####
1:1	
Content: Bottom	Size A3
Date: 4/22/2025	

F

Three point bending test data

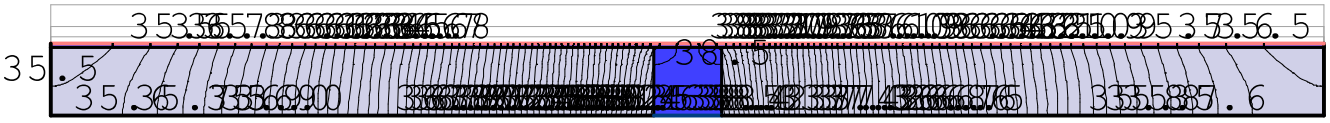
3point bending test

between supports
40 mm

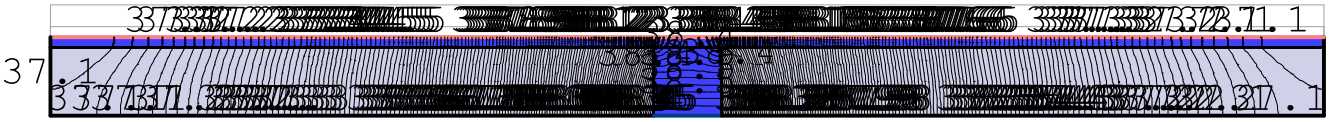
num.	Sample	dim.	b [mm]	h [mm]	l [mm]	I [mm4]	max.	N	flex.	load deflection (N/mm)	σf Flexural strenght (MPa)	Ef Flexural modulus (GPa)
1	B.150.700		10,8	12,6	50	1,44E+13		195		909,3	6,8	0,67
2	B.150.700		10,8	13,3	50	2,76E+13		210		826,6	6,6	0,52
3	B.150.700		10,5	12,9	50	1,86E+13		328		1243,1	11,3	0,88
4	B.150.700		10,7	13,1	50	2,28E+13		294		1330,2	9,6	0,88
5	B.150.700		10,7	13,1	50	2,28E+13		197		1217,0	6,5	0,81
6	B.150.750		11,0	13,7	50	4,01E+13		369		1135,5	10,7	0,64
7	B.150.750		10,7	13,6	50	3,57E+13		259		919,9	7,8	0,55
8	B.150.750		10,9	14,1	50	5,61E+13		173		472,2	4,8	0,25
9	B.150.750		10,7	14,3	50	6,52E+13		274		797,1	7,5	0,41
10	B.150.750		10,8	13,7	50	3,93E+13		315		1045,2	9,3	0,60
11	B.200.700		10,8	12,3	50	1,03E+13		454		1023,8	16,8	0,83
12	B.200.700		11,3	12,2	50	1,02E+13		375		909,7	13,4	0,71
13	B.200.700		10,9	12,3	50	1,09E+13		312		1300,3	11,3	1,03
14	B.200.700		11,0	13,4	50	3,07E+13		570		1310,0	17,3	0,79
15	B.200.700		10,8	12,5	50	1,25E+13		105		555,3	3,7	0,43
16	B.200.750		11,1	14,9	50	1,11E+14		665		1033,4	16,2	0,45
17	B.200.750		11,0	14,2	50	6,16E+13		708		1373,9	19,2	0,70
18	B.200.750		10,9	12,3	50	1,09E+13		539		1321,0	19,6	1,04
19	B.200.750		10,8	12,3	50	1,08E+13		961		1820,0	35,3	1,45
20	B.200.750		10,8	12,7	50	1,58E+13		274		921,5	9,5	0,67
21	B.250.700		11,1	11,8	50	6,74E+12		463		1545,5	18,0	1,36
22	B.250.700		11,3	11,6	50	5,59E+12		326		1538,4	12,9	1,40
23	B.250.700		11,1	12,1	50	9,11E+12		436		1892,1	16,1	1,54
24	B.250.700		11,0	11,5	50	4,90E+12		540		1432,4	22,3	1,37
25	B.250.700		10,9	12,4	50	1,20E+13		461		2006,5	16,5	1,54
26	B.250.750		11,1	11,3	50	3,83E+12		1176		2818,9	50,4	2,86
27	B.250.750		11,4	10,7	50	2,14E+12		905		2045,7	41,6	2,34
28	B.250.750		10,8	12,1	50	8,86E+12		683		1950,0	25,9	1,63
29	B.250.750		10,9	11,8	50	6,62E+12		743		1672,4	29,4	1,49
30	B.250.750		11,0	11,2	50	3,38E+12		815		2009,3	35,8	2,11

G

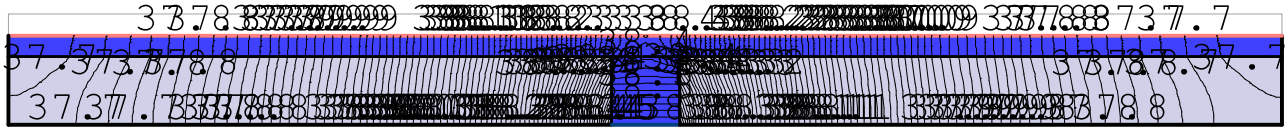
Thermal resistance for different layer thicknesses of aluminium



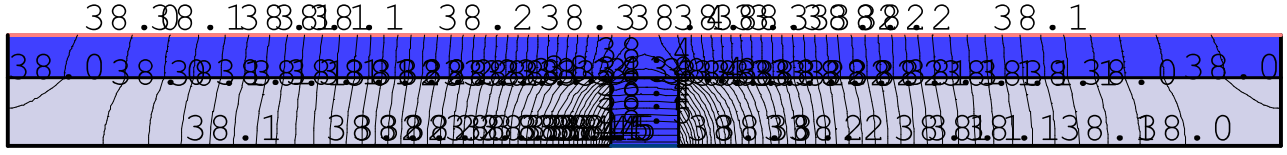
1.0 mm layer thickness



2.5 mm layer thickness



5.0 mm layer thickness



10.0 mm layer thickness

10.0 mm layer thickness, vinyl finish flooring

H

Load case for facade panel

Panel

Lenght	l	0,3	m
Width	b	0,3	m
Surface	A	0,09	m^2
Density	*ρ*	2200	kg/m3
Mass	*m*	0,62	kg

Loads

Windload	*Fw*	1,5	kN/m^2
Safetyfactor	*γw*	0,75	

Material

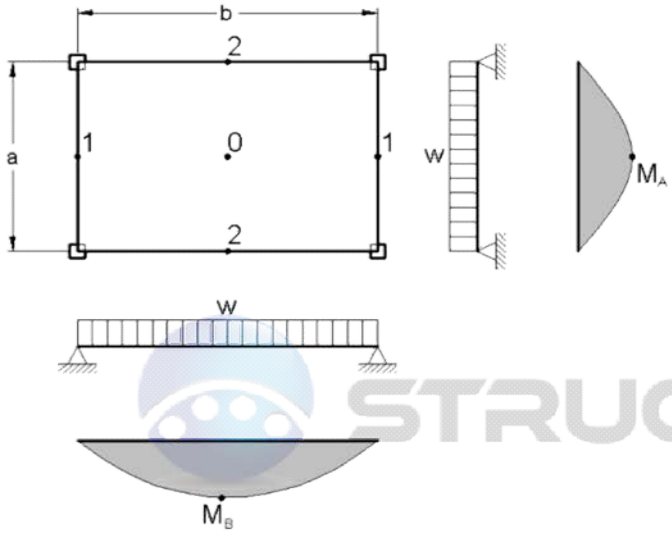
Bending strenght	*σdesign*	50	Mpa
Material factor	*γm*	1,5	

Bending moment

M0	=	$\alpha_{0(a)} F_w b^2$	**9,6 Nm**
M1	=	$\alpha 1_{(a)} F_w b^2$	**16,3 Nm**

Profile section

H	=	$\sqrt{6M*\gamma m / b*\sigma design}$	**3,12 mm**



Bending Moments

$$M_{0(a)} = \alpha_a w b^2$$

$$M_{0(b)} = \alpha_b w b^2$$

$$M_{1(a)} = \alpha_{1(a)} w b^2$$

$$M_{2(b)} = \alpha_{2(b)} w b^2$$

Maximum Deflection

$$\Delta_0 = \eta_0 w \frac{b^4}{D}$$

$$\Delta_1 = \eta_1 w \frac{b^4}{D}$$

$$\Delta_2 = \eta_2 w \frac{b^4}{D}$$

$$D = \frac{Et^3}{12(1-\mu^2)}$$

a/b	$\alpha_{0(a)}$	$\alpha_{0(b)}$	$\alpha_{1(a)}$	$\alpha_{2(b)}$	η_0	η_1	η_2
1.0	0.0947	0.0947	0.1606	0.1606	0.0262	0.0172	0.0172
0.9	0.0689	0.1016	0.1367	0.1541	0.0218	0.0119	0.0164
0.8	0.0047	0.1078	0.1148	0.1486	0.0180	0.0079	0.0157
0.7	0.0289	0.1132	0.0955	0.1435	0.0158	0.0050	0.0151
0.6	0.0131	0.1178	0.0769	0.1386	0.0148	0.0030	0.0146
0.5	0.0005	0.1214	0.0592	0.1339	0.0140	0.0016	0.0141

$\alpha_{0(a)} F_w b^2$ $\alpha_{0(b)} F_w b^2$ $\alpha 1_{(a)} F$ $\alpha 1_{(b)} F_w b^2$

0,0947 0,0947 0,16 0,1606

Panel

Lenght	l	0,6	m
Width	b	0,6	m
Surface	A	0,36	m^2
Density	*ρ*	2200	kg/m3
Mass	*m*	3,50	kg

Loads

Windload	*Fw*	1,5	kN/m^2
Safetyfactor	*γw*	0,75	

Material

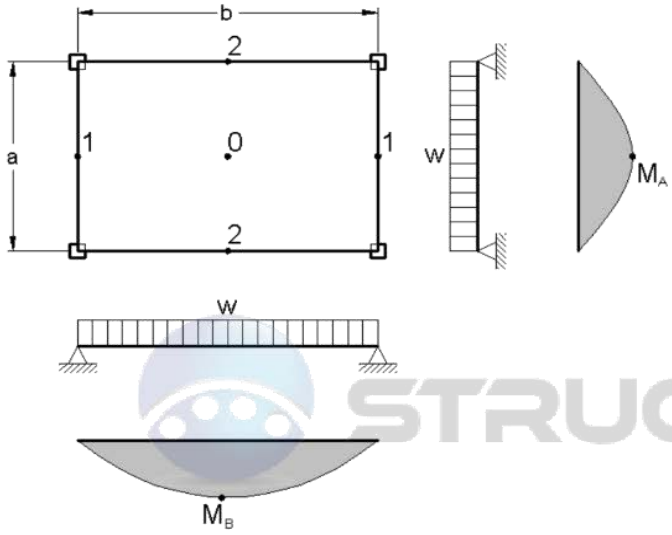
Bending strenght	*σdesign*	50	Mpa
Material factor	*γm*	1,5	

Bending moment

M0	= $\alpha_{0(a)} F_w b^2$	**38,4**	**Nm**
M1	= $\alpha 1_{(a)} F_w b^2$	**65,0**	**Nm**

Profile section

H	= √6M*γm / b*σdesign	**4,42**	**mm**



Bending Moments

$M_{0(a)} = \alpha_a w b^2$

$M_{0(b)} = \alpha_b w b^2$

$M_{1(a)} = \alpha_{1(a)} w b^2$

$M_{2(b)} = \alpha_{2(b)} w b^2$

Maximum Deflection

$\Delta_0 = \eta_0 w \frac{b^4}{D}$

$\Delta_1 = \eta_1 w \frac{b^4}{D}$

$\Delta_2 = \eta_2 w \frac{b^4}{D}$

$D = \frac{Et^3}{12(1-\mu^2)}$

a/b	$\alpha_{0(a)}$	$\alpha_{0(b)}$	$\alpha_{1(a)}$	$\alpha_{2(b)}$	η_0	η_1	η_2
1.0	0.0947	0.0947	0.1606	0.1606	0.0262	0.0172	0.0172
0.9	0.0689	0.1016	0.1367	0.1541	0.0218	0.0119	0.0164
0.8	0.0047	0.1078	0.1148	0.1486	0.0180	0.0079	0.0157
0.7	0.0289	0.1132	0.0955	0.1435	0.0158	0.0050	0.0151
0.6	0.0131	0.1178	0.0769	0.1386	0.0148	0.0030	0.0146
0.5	0.0005	0.1214	0.0592	0.1339	0.0140	0.0016	0.0141

$\alpha_{0(a)} F_w b^2$ $\alpha_{0(b)} F_w b^2$ $\alpha 1_{(a)}$ F $\alpha 1_{(b)} F_w b^2$

0,0947 0,0947 0,16 0,1606