Eidgenössische Technische Hochschule Zürich
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Materials Science and Technology

Semester Thesis

# Ultra-Lightweight Design for Metal Additive Manufacturing

## Development of an Ultralight Moka Pot

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**Supervised by:**
Prof. Edoardo Mazza
Dr. Ehsan Hosseini

**Author:**
Luca Hasler

# Declaration of Originality

I hereby declare that the written work I have submitted entitled

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is original work which I alone have authored and which is written in my own words.

**Author(s)**

| | |
|---|---|
| Luca | Hasler |

**Student supervisor**

| | |
|---|---|
| Ehsan | Hosseini |

**Supervising lecturer**

| | |
|---|---|
| Edoardo | Mazza |

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# Preface

I would like to thank my supervisor Ehsan Hosseini for his valuable coaching during this thesis. My gratitude goes Irene Ferretto for her continued support in the manufacturing process. I also wish to express my appreciation to Prof. Mazza for the opportunity to work in the Experimental Continuum Mechanics Lab of EMPA.

# Abstract

The aim of this project is to improve the design of a conventional moka pot to make it more suited for outdoor use by making it significantly lighter in weight, more compact, as well as more functional. These improvements are made by leveraging the potential of metal additive manufacturing as a promising new manufacturing technology. The geometry is optimized structurally, functionally and for manufacturability. A first print is then manufactured to test the system's performance.

# Acronyms and Abbreviations

| | |
|---|---|
| AM | Additive Manufacturing |
| DFAM | Design For Additive Manufacturing |
| EDM | Electric Discharge Machining |
| EMPA | Eidgenössische Materialprüfungs- und Forschungsanstalt |
| ETH | Eidgenössische Technische Hochschule |
| FDM | Fused Deposition Modelling |
| FEM | Finite Element Method |
| MAM | Metal Additive Manufacturing |
| SLM | Selective Laser Melting |

# Chapter 1

# Introduction

## 1.1 Motivation

One part of the motivation for this project came from a strong interest in additive manufacturing, especially in exploring the field of design for additive manufacturing (DFAM), including both its potential as well as its specific challenges. After having worked extensively with simpler 3D printing technologies such as fused deposition modelling (FDM), the author wanted to tackle the more complex challenge of designing a part for metal additive manufacturing (MAM), and more specifically selective laser melting (SLM). The other aspect of motivation is more personal. In the last few years, the author has grown increasingly interested in a type of hiking called "thruhiking". It involves backpacking for long distances, through countries or entire mountain ranges, completely self-supported for weeks or even months at a time. That means hiking well over thirty kilometers every day while carrying a tent, a sleeping bag and food, basically all one needs to survive outdoors, in a backpack. Therefore, the weight of every piece of equipment is crucial, the lighter the backpack, the further and more comfortably one can hike in a day. Which leads to problem: Many hikers do enjoy a freshly brewed cup of coffee in the mountains, especially on a rainy day where getting out of one's sleeping bag may just be a bit harder than usual. However, the lightest possible setup which brews coffee of acceptable quality for many is a Bialetti moka pot. And weighing in at 475 g for the brewer and a cup (excluding the stove), it cannot exactly be considered "ultralight" (for reference, a typical backpacking setup without the Bialetti, but including all else, weighs in at six kilograms). A Bialetti is also quite bulky by taking up roughly 2.5 L of backpack space. This lead to the idea of combining these two areas of interest and use MAM to design an ultralight moka pot which would be suitable for thruhiking.

## 1.2 Project Goal

As already stated above, the goal of this project is to develop a lightweight and compact moka pot, while leveraging the potential of metal additive manufacturing to increase its functionality for outdoor use. A secondary goal, or rather challenge in this project is to produce a functional prototype with the very first full scale metal print in an attempt to show the potential of DFAM . The quality of the produced coffee shall remain comparable to that produced by an original Bialetti. Furthermore, all coffee related parameters are kept constant, and they are not within the scope of the optimisation process. At this point it has to be clearly stated that applying MAM to a consumer product such as a Bialetti makes only limited sense due to its relatively high cost. This project does not intend to develop a marketable product, but it rather serves as a technology demonstration for the potential of MAM. Applying the same development methodology to a different industry, perhaps the aerospace sector, where a decrease in weight is worth more money, suddenly can make this approach lucrative.

## 1.3 Bialetti Anatomy

In the following section, the different elements and general working principle of a conventional moka pot, in this case a Bialetti, will be presented. This type of coffee brewer consists of two major parts as can be seen in figure 1.1. A lower reservoir which also contains a removable, funnel shaped, powder basket and an upper reservoir containing a riser tube. Both are connected though a threaded locking element which seals against a gasket mounted in the upper reservoir. During operation, the lower reservoir, henceforth referred to as the "boiler, is partially filled with water and placed on a heat source. This will lead to some of the water evaporating. The increased pressure of the hot steam then forces the water upwards through the powder basket, thereby extracting the coffee. The coffee then continues to flow through a small sieve to stop coffee grounds and into the riser tube. Once it reaches the top of this "riser" it then overflows into the upper reservoir, or "cup", where it is collected. This leads to the characteristic bubbling sound which can be heard once coffee extraction is finished. Due to the bubbling a lid is required as well to stop the coffee from sputtering out of the cup while flowing out of the riser. Finally, the boiler contains a safety relief valve to limit the generated steam pressure in case of a blocked system which can be caused by the coffee being ground too finely.

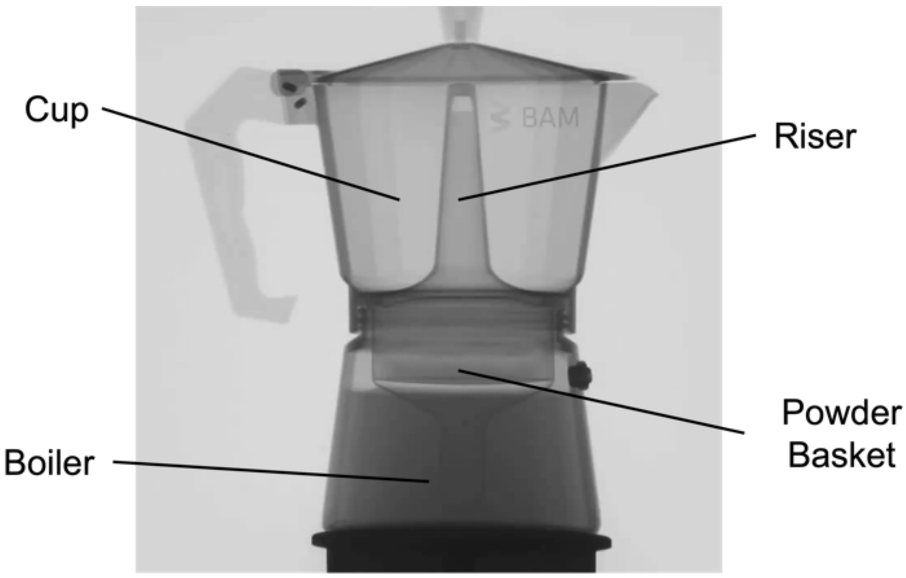



Figure 1.1: Bialetti CT Scan [1]

# Chapter 2

# Methodology

## 2.1 Design Approach

As already mentioned in section 1.2 one of the challenges which was set for this project is that the first full scale metal print should be functional. In order to meet this goal an agile development strategy was chosen. Agile design involves an iterative approach to problem solving. So called ”sprints” are performed in order to push the development process forward. Design problems are identified, and instead of moving forward based on assumptions or hope, a quick way of exploring that uncertainty is employed. That could involve fashioning a low fidelity prototype to test the functionality of a part, or it could involve an experiment or a simulation to confirm an assumption about the physical behaviour of it. And although these were two examples of positive outcomes, failure is also very much an accepted outcome in a design sprint. The key takeaway is that at the end of an iteration something about the initial problem is learned and an informed decision can be taken to move the design forward into the next stage. A visual representation of this approach can be seen in figure 2.1, which shows both the conceptual approach as well as the actual design history of this project, and all its prototypes of different fidelities. This leads both to a fast and especially to a robust design process with a much higher change of a working final design than employing a traditional cascading design mentality.

Figure 2.1: Agile Design - A Visual Representation

## 2.2 Prototyping Tools

Agile design relies heavily on rapid iterations through fast prototyping and testing. In this project two methods were applied to further increase the productivity in this regard. They are briefly explained below:

### 2.2.1 Exploiting Similarities

One of the delimitations mentioned in section 1.2 is that all coffee related parameters of the Bialetti are kept constant. Specifically, this implies that the following parameters remain unchanged:

- The boiler volume and its air-water ratio
- The powder basket volume and shape
- The hole pattern in both the powder basket as well as the upper sieve
- The riser diameter

This decision is not only taken to preserve the quality of the coffee produced by that particular moka pot, but it also has two additional benefits: Firstly, it allows for original Bialetti off-the-shelve parts to be used for components which need to be replaced regularly, such as the gasket. This also solves the particular problem of finding a supplier for high-temperature, food-safe gasket materials. Another reason for using original parts for these elements was discovered during testing: Changing the hole pattern even slightly leads to a dramatic decrease in coffee quality. A second, and much more important benefit comes from the fact that this leads to the coffee brewing process working more or less unchanged between a Bialetti and the design being developed here. This similarity can be exploited heavily in early testing to measure process parameters and also to explore the effects of small functional design changes by simply manipulating a stock Bialetti and observing its behaviour. This in turn is both much cheaper and quicker than to manufacture an entirely new prototype for every iteration. This is another aspect of the development strategy employed, aimed at producing a functional first full scale print. Several examples of its application will be presented in chapters 3 and 4.

### 2.2.2 Prototyping Fidelity

Careful consideration has to be made regarding the choice of prototyping method and fidelity. For instance, in this project the use of low fidelity FDM additive manufacturing has been instrumental, as can easily be observed in figure 2.1. The promises of applying this technology seem obvious. Fast lead times, extremely low cost, and the possibility of a desktop setup (instead of a dedicated workshop) to name but a few. In many aspects FDM can satisfy the needs of a developer perfectly well, however when applying such a prototyping technology it is important to also be aware of its limitations. This is especially important if designing for metal additive manufacturing using FDM prototypes: Both tools are additive manufacturing technologies, sharing many common design rules.[1] Designing a successful FDM test part therefore generally promises success in printing using MAM as well. But only up to some extend, as some explicit differences between the two technologies exist. Careful attention has to be paid to them to prevent a false sense of security regarding the manufacturability of a part. Furthermore, the performance of a certain design elements also needs to be evaluated with careful attention placed on the

[1] For instance, walls angled more than 45 degrees from vertical require support

effects of it being manufactured with FDM or MAM.

Typically, the polymer prototypes obtained by FDM prints are well suited for many applications such as:

- Functional testing
  - The handling of the product
  - Fluid flow properties
- User experience design
- Visual design

Some of the shortfalls include the following properties:

- Poor mechanical properties
- High temperature functional testing is not possible
- Different surface roughness
- Tolerances are different compared to parts printed by MAM

In this project some of the limitations of FDM prototyping were mitigated by exploiting the similarities to a stock Bialetti as explained in subsection 2.2.1 whenever high mechanical loads or temperatures were present. In the specific case of the newly designed, additively manufactured, locking element between boiler and cup, both the surface roughness as well as the tolerances were identified to be critical parameters for the operation of the mechanism. Therefore, after using FDM prints to validate the general functional principle, a single metal test print of this assembly was manufactured to gain confidence in its final performance with the given dimensions. The final prototypes using both materials, can be seen in figure 2.2 (FDM on the left, SLM on the right). Details regarding the development of the locking element follow in chapter 4 describing the conceptual design.

Figure 2.2: Different Prototyping Fidelities

# Chapter 3

# Requirements

Now follows a clearer, more detailed and structured set of requirements which serve to guide the development process. Later they can also be used as a benchmark for evaluating the system's performance. First, the requirements themselves will be presented, followed by a more detailed explanation of how they were derived.

## 3.1 System Requirements

### 3.1.1 Design Requirements

Design requirements serve to control the general design of the product as well as its performance. These are the key elements which are also represented in the project goal:

- The product should be lightweight.
- The product should be compactly stowable.
- The product should be optimized for additive manufacturing:
  - It should require as little post processing as possible, specifically no machining operations.
  - It should leverage the unique potential of AM.

### 3.1.2 Functional Requirements

Functional requirements define features that serve the user's needs. They shape the product's functionality:

- The product should produce coffee of similar quality as a standard Bialetti moka pot.
- The user should be able to manipulate the pot even when hot.
- The user should be able to consume the coffee easily in at least one of the following two ways:
  - The user should be able to cleanly pour coffee into a separate cup.
  - The user should be able to safely drink coffee directly from the upper reservoir.
- No coffee should be spilled during brewing.

- Upper and lower container should be connected via a releasable and sealable connection.
- A fail safe method to limit the brewing pressure in case of a blocked riser should be implemented.

### 3.1.3 Performance Requirements

These requirements shape the product's quantitative performance wherever applicable:

- The internal volume of the boiler should be 230 ml.
- The produced coffee volume should be 150 ml.
- The boiler should be able to sustain 2.25 bar in regular operation.
- The boiler should be able to sustain up to 4.5 bar in case of a blocked riser.
- The global maximal temperature of the internal working fluids is 100°C.

### 3.1.4 Environmental Requirements

Environmental requirements define the conditions under which the product must be able to operate reliably:

- The product should be able to operate at varied environmental temperatures that can be expected during four season outdoor use (-20°C to 40°C).
- As an outdoor product, the system should be resistant to corrosion

### 3.1.5 Interface Requirements

The system is designed to work with off-the-shelve Bialetti replacement parts and commercially available backpacking stoves. As such it is subject to two interface requirements:

- The minimum base diameter must be at least 70 mm.[1]
- The boiler opening must be exactly 58 mm in diameter to accept the stock Bialetti powder basket.

## 3.2 Generating Thermo-Mechanical Requirements

From a structural standpoint, this moka pot has two opposing driving forces: On one hand the project goal demands a lightweight solution, and therefore as little material as possible. On the other hand, the entire design has to be structurally sound to allow safe and reliable operation. Finding a solution which is just strong enough for the applied loads promises to be an optimal solution. In order to find this design, it is important to accurately understand both the thermal and structural loads present on the structure (see performance requirements in subsection 3.1.3). Calculating or simulating clear requirements would be a non-trivial task especially for the boiler due to these circumstances:

[1] This requirement is based on the minimal diameter an object needs to rest on a gas stove in a stable fashion. It was generated by measuring the diameters required by a selection of readily available backpacking stoves at an outdoor store.

- Thermal load:
  - The boiler sits directly on an open flame (stove).
  - The boiler is not insulated and experiences conductive, convective and radiative heat losses.
  - It is filled with water which eventually flows out of the boiler (thermal transfer due to mass flow).
- Mechanical load:
  - The steam pressure inside is directly linked to the thermal load.
  - The maximum steam pressure is regulated by the coffee grounds acting as a valve with uncertain parameters

The workaround to this problem lies in exploiting the similarities to a stock Bialetti, as discussed in subsection 2.2.1. Due to the fact that the coffee brewing process remains unchanged, the internal fluid temperatures and pressures can simply be measured by attaching a pressure transducer[2] and thermocouples[3] to the boiler, as can be seen on the left side in figure 3.1. The respective pressure and temperatures can then be recorded using a data acquisition device[4] while brewing several coffees. Additionally, thermocouples were spot welded to the bottom of a thin-walled titanium cup boiling some water, to investigate the temperatures on the external surface. In this way, accurate temperatures and pressures for real life coffee brewing could be measured with relatively low effort and high certainty in accuracy. Typical results for one run of such a brewing experiment can be seen on the right side in figure 3.1. The internal fluid temperature rises steadily from ambient temperature to 100°C, the natural limit of a boiling fluid. It can also be seen that the pressure remains at atmospheric pressure for the first half of the brewing cycle. Later it rises sharply to roughly 2.25 bar, before decreasing again as soon as the extraction process is finished (indicating that the coffee grounds lose their pressure sealing properties once coffee has been extracted).

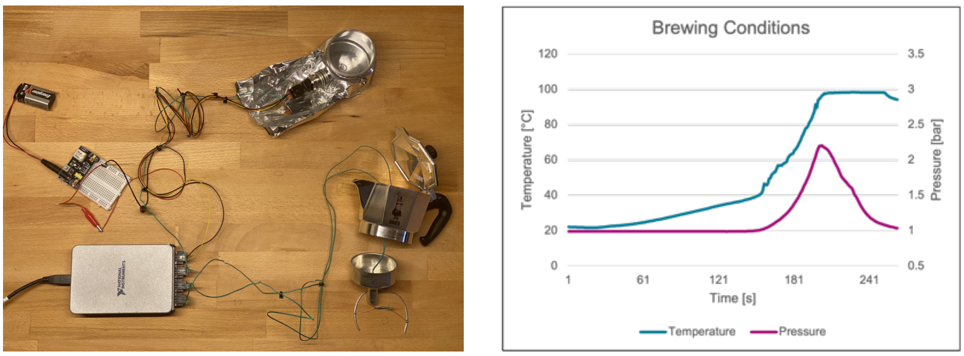



Figure 3.1: Instrumentation and Results of Brewing Parameter Measurements

[2]Honeywell MIPAM1XX004BAAAX
[3]K-type
[4]NI-9219 used together with NI DAQ Express

# Chapter 4

# Conceptual Design

This chapter will describe the early stages of design according to the methodology presented in chapter 2. It will show how the design space was explored for different solution variations, how they were evaluated and finally concludes in a first full-scale unrefined prototype.

## 4.1 Identifying Design Elements

The first step in starting to design this moka pot is to take a step back and to understand the morphology of the system. This allows one to explore, discover and get an overview of the problems which need to be solved in a later step. In this particular case most of the work in identifying all the design elements of a moka pot has already been done in analysing a Bialetti (see section 1.3). The result of this effort can be seen in figure 4.1, which displays all major elements of a moka pot in a problem-oriented way, intentionally drawn completely detached from potential solutions, but in a way which allows an easy understanding of the problem at hand.

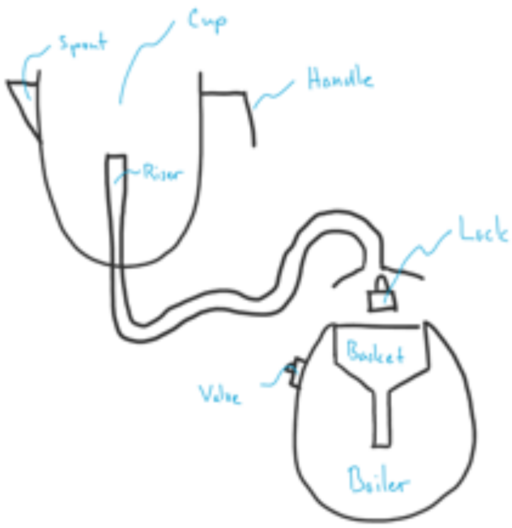



Figure 4.1: Identified Design Elements

## 4.2 Ideation: Generating Different Concepts

After identifying all design elements in the previous section, now comes the time to shift the focus on exploring the design space for different solutions to every identified challenge. This step is still largely decoupled from practical aspects such as manufacturability or reliability of a design. Every idea is acceptable as long as it is solution oriented as the goal is to develop a broad set of different ideas. A brief visual representation of this can be seen in figure 4.2, which displays sketches of all developed solutions. In the following, some of the different ideas will be summarized. A more detailed representation can also be found in appendix A.

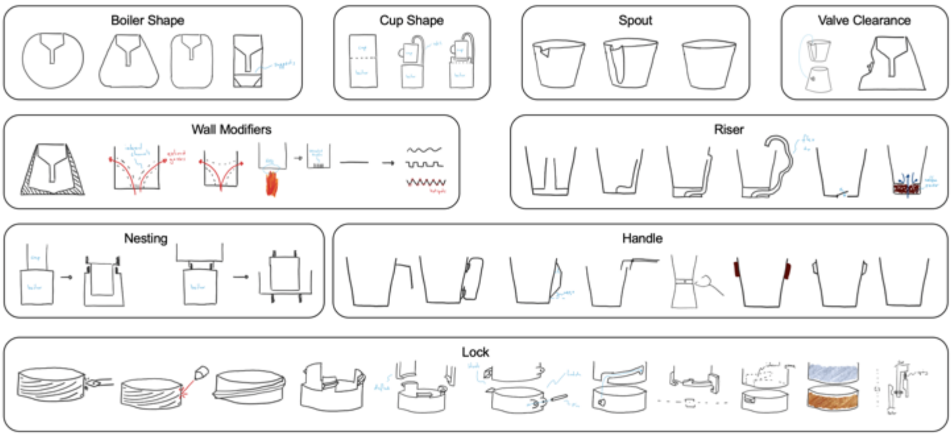



Figure 4.2: Proposed Conceptual Solutions

**Nesting:**

One aspect of design is concerned with nesting the boiler and cup inside of each other. If this is achieved, this would lead to a dramatically smaller stowed volume fulfilling one of the design goals. The question here is which way around the nesting should be done, especially considering which dimensions are constrained for both parts.

**Boiler Shape:**

Several possible solutions for the boiler shape are proposed. As the boiler is acting as a pressure vessel, all are intended to deal with this pressure in a beneficial way. Pressure-wise a spherical tank immediately comes to mind; however, this doesn't appear very practical. Variations of this are cylindrical and cone shaped pressure vessels with rounded edges to reduce stress concentrations and improve manufacturability as well as functionality. Finally, due to the use of AM, it is possible to easily add internal supporting ribs independent of the chosen shape, should the need arise.

**Cup Shape:**

In general, the cup shape allows for a lot more design freedom as there are fewer constraints. The conceptual decision at this point is therefore considering if the cup should be an integral element of the moka pot or if there merely should be space for a separate, off-the-shelve lightweight backpacking cup, which could be used for different applications as well. With this approach some of the design freedom of the cup would be lost again, and provisions for a separate riser tube would have to be made. If the cup is to be an integral part of the system, then provisions should be made that one can drink directly from it, instead of pouring the collected coffee into a separate cup as is the case with the stock Bialetti, thereby fulfilling two functions with one component and saving weight and volume.

**Lock:**

The locking mechanism is one of the crucial and most challenging design elements with regards to functionality and especially manufacturability. Figure 4.2 shows a large number of different ideas, ranging from traditionally machined threads and several different ideas for thread-like and snap fit mechanisms which could be used as printed, to more novel ideas such as a self-sealing connection based on two parts made out of materials with different thermal expansion coefficients.

**Riser:**

All concepts for the riser revolve around the fact that the central stock Bialetti riser is an obstruction both for nesting as well as for drinking directly from the cup. Some of the proposed solutions exploit the design freedom of MAM to move the riser out of the way towards the side walls. Finally, two solutions are brought forward, which remove the riser completely by using either a valve or the coffee grounds themselves to allow liquid to flow into the cup but not back down into the boiler. If these two solutions are practically feasible remains to be seen.

**Splash Guard:**

In the Bialetti anatomy (section 1.3) it is mentioned that a lid is needed to stop coffee from sputtering out of the cup. Instead of a lid an integrated splash guard could be used. Potentially, the coffee could also be redirected in the top of the riser so that it would be ejected downwards into the cup. Both solutions would decrease weight and volume, accommodate nesting and drinking from the cup and decrease complexity of the system.

**Handle:**

Several different handle designs of different complexity are proposed. These involve traditional handle designs resembling the stock Bialetti or foldable metal handles (either printed in place or assembled after the fact). Two ideas involve an additional part to grip the coffee brewer, including the possibility that this part also serves as an element of the locking mechanism. Additionally, several low profile designs are suggested using materials of low thermal conductivity (wood, leather, titanium) to fashion a simple heat-brake-style handle, which simply insulates the cup sufficiently to grab it. The titanium version could likely be directly printed, potentially even support free. However its thermal conductivity is significantly higher than that of the other materials, and its ability to sufficiently insulate the handle is less certain.

**Valve Clearance:**

One particular problem if the boiler is nested in the cup arises from the safety valve which is added to the boiler to act as a fail-safe pressure limitation. Some way must be found to accommodate it into the design to still allow for efficient nesting. Two solutions are proposed: Either the valve could be mounted in a recessed area of the boiler, or it could be mounted flush, and a recess could be made in the cup to allow sufficient clearance.

**Spout:**

It is debatable if a spout for pouring coffee is required at all, considering that the cup itself could be used to drink the coffee. It would be an additional feature in case the coffee should be shared at camp, however, it is not a priority. One proposed solution is to shape the spout in a way that it also acts as a notch to allow for valve clearance.

**Wall Modifiers:**

Finally, some concepts for modifying the profile of the boiler independent of its shape are suggested as well. These are all examples of using the extended design freedom of additive manufacturing to increase the functionality of the printed part at almost no extra cost. It is suggested to gradually vary the wall thickness to optimize the material use depending on local stresses. Another possibility exists to add internal channels for hot gasses to flow through the boiler, increasing its surface area and thereby the heat transfer efficiency from the gas stove. Finally, a similar effect could also be achieved by simply printing a corrugated wall profile or heat fins.

## 4.3 Converging on a Solution: Evaluation

Having concluded the divergent phase of conceptual design as described in the section above, the goal in this step is to converge on a single or a few solutions which appear most promising. For this, two approaches were used: In some cases, the riser for instance, the feasibility of a promising solution was unclear. Wherever possible, these solution attempts were either confirmed to be working or not by running a quick experiment, employing low fidelity prototypes, and exploiting similarities in performance to the stock Bialetti. In other cases, such as the boiler shape, several options appeared feasible. In these cases, a more analytical approach was chosen to evaluate the possible solutions. These evaluations are presented for each design element below:

**Nesting:**

The design choice for nesting can be made by analysing the relevant constrained dimensions of the geometry (see requirements, subsection 3.1.1):

- Boiler:
  - Base diameter: Minimum 70 mm
  - Top diameter: Approximately 60 mm[1]
  - Boiler volume: 230 ml
- Cup:
  - Base diameter: Approximately 60 mm, larger than boiler top diameter
  - Cup volume: Minimum 150 ml

[1] Lock internal diameter (58 mm) and wall thickness

In general, it can be stated that the shape of the boiler is much more constrained due to having fixed top and bottom diameters, and a fixed volume. Additionally, it has to be optimized as a pressure vessel. The cup on the other hand only has a fixed bottom diameter and a minimal volume, its shape is not driven by any External factors. A first observation can be made that the volume ratio of boiler to cup is approximately three to two. Naturally this would suggest nesting the smaller cup inside of the bigger boiler. However, further analysis of the constrained diameters reveals a problem: In order for the lock to function and seal properly, the boiler must have the smaller diameter male end, which in turn receives the powder basket.[2] This means that the lock diameter of the cup would be larger than the opening in the boiler. The bulk of the cup however would have to be narrower than the opening in the top of the boiler to allow for nesting. This would lead to a tall and narrow cup. The boiler on the other hand also has a constrained base diameter and fixed volume which in turn forces a maximum height which is below the minimum height of the tall and narrow cup. It therefore becomes evident that this arrangement results in an inefficient nesting performance. Stacking the two parts the other way around, however, opens up more possibilities, especially as the design freedom of the cup's shape can be exploited to aid nesting by closely following the profile of the boiler and the cup top opening can be matched to the maximum required diameter to stow the boiler in it efficiently. An additional benefit of this stacking configuration is that the powder basket can be stored in the boiler also in the stacked configuration, something which would be impossible if nesting was achieved the other way around.

**Boiler Shape:**

The boiler shape is one of the key challenges in this design as it is subject to several requirements which force different geometries as optimal solutions. An analytical evaluation approach is therefore chosen. A spherical shape would be the best solution from a mechanical standpoint, however it is disadvantageous for manufacturing, for nesting with the cup as well as generally in terms of user handling (unstable base). A cylindrical boiler with rounded edges promises better nesting and handling, however, still causes problems with regards to additive manufacturing due to the horizontally overhanging top surface which would require internal support structures. Coincidentally, a cone shaped boiler, similar to the original Bialetti shape, seems to be a promising trade-off between manufacturability and mechanical performance. The latter can be greatly improved by rounding over the bottom sharp corner with a large radius. It also facilitates nesting the boiler in the cup efficiently due to its compliant stacking behaviour.[3] Additionally, the bottom radius size is also driven by nesting: In order to achieve compact and efficient nesting the cup needs to follow the profile of the boiler closely. This can only be realized if the boiler sidewall is convex for the entire height of the cup. From the volume ratio of boiler and cup, and their similar shape, it follows that the boiler must be convex for about its upper two thirds, leaving space for a radius in the lower third. The precise value can later be calculated while designing the model in CAD and should also account for some extra volume in the cup to ease in handling and drinking.

[2] Reverting this polarity would require a much more complex double wall design, with the gasket also integrated into the boiler, clearly an inefficient solution.

[3] Two nested cylinders need well matched diameters and tolerances to stack snugly and without being overly loose. Two cones can just be pushed inside of each other until the sides make contact, with only their angle being critical.

**Cup Shape:**

From the two paragraphs above it becomes evident that an integrated cup is required. This also aligns well with the general design philosophy of creating a standalone product which can act as a self-contained system apart from a stove. The geometrical shape is directly driven by the cone shape of the boiler, to allow for efficient stacking.

**Lock:**

Designing a reliable, additively manufactured locking mechanism is one of the core challenges of this project. The following description aims to explain the design decisions regarding this challenge. To design a successful locking mechanism, it must fulfil two requirements: It has to establish a sealed, gas tight connection between the two parts reliably, and if at all possible, it should be designed to be functional as printed, with as little or no post processing.
Analysing the different proposed solutions with regard to the first requirement in more detail quickly shows some major differences in reliability and functionality. As the boiler seals axially against the gasket in the cup, the locking mechanism needs to provide an axial compression force. With time, the gasket wears down slightly and loses some of its elasticity. Ideally the locking mechanism should therefore provide some compliance in axial positioning, to allow the two parts to reliably seal. Consequently, thread-like designs promise to be far more successful than any other type of locking system, due to the fact that the two parts can simply be rotated as far into each other as required by compliance to establish a gas tight seal. It also becomes evident that a continuous upper edge on the boiler side becomes important, as it is one part of the sealing interface. Threaded systems also provide this feature. The remaining threaded locking systems are now evaluated regarding their manufacturability, with a special focus on usability as printed. One approach which certainly promises a reliable functionality, is printing an over-sized circular profile and machining conventional threads after printing. However, this approach violates the additive manufacturing design requirement to avoid machining (see subsection 3.1.1). Another option is to attempt to print regular threads directly, something which is sometimes done in FDM, however has no precedent in MAM, most likely due to the higher surface roughness which could cause the threads to seize. This leaves an over-sized additively manufactured thread (which can have much looser tolerances than a smaller one, to account for surface roughness) as the most promising solution. Instead of a continuous male thread, which would require a continuous helical counterpart, a partial, bayonet-style, thread is suggested. This saves space and weight, as the female thread can also start off vertically before transitioning into the helical sweep, making it more compact and better applicable to the case of a moka pot lock. This design ends up resembling a portafilter bayonet thread, as it is used in espresso machines. This precedent gives hope that the design will functionally perform as expected. It is further possible to adapt this design to additive manufacturing by utilizing a thread profile with sides angled at 45°, which are fully self-supporting and do not require any support and therefore also almost no post processing. It can also be realized in a lightweight fashion by using the design freedom of additive manufacturing: Instead of a recessed groove in a cylindrical wall resulting in a thicker structure, the entire thin wall can be shaped as the female thread (see figure 4.3). This approach could also be used to reduce the weight of the male profile, however as it is only a much shorter profile, the material is kept for structural reasons. By tilting the sides of the profile, this thread also becomes self-centring, meaning that generous tolerances can be used to allow easy operation, despite the inherent surface roughness of MAM.

After converging on this hypothetical solution, verifying the lock's practical performance is very important, as it is a critical element in the functionality of the entire design. An initial quick prototype manufactured with FDM 3D printing validated the general idea. However, as already described in subsection 2.2.2, in case of the locking mechanism, an FDM prototype is insufficient, as the design's performance is heavily dependent on both surface roughness and tolerances. Therefore, a second, small scale metal prototype was manufactured to gain confidence in the design. Fortunately, it worked very well. With this confidence, development could continue.

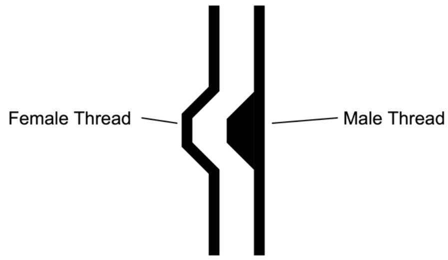



Figure 4.3: Lightweight Thread Profile Designed for AM

Finally, the exotic solution based on inhomogeneous thermal expansion coefficients is unfortunately not feasible, as in the given part dimensions and temperatures, the difference in thermal expansion of the available materials is less than the surface roughness produced by MAM. This prevents this connection from being releasable. Additionally, it's unclear whether or not such a seal would be gas tight.

**Riser:**

After choosing a nesting strategy it is evident that a central riser is an obstruction. As described in the previous section several possible solutions to this exist by either moving the riser to the side or removing it altogether. The latter strategy was explored first as it would be the most efficient in terms of weight and space: A market review of food safe, small scale check valves with suitable opening pressure revealed that unfortunately no convenient solution is readily available. This valve could potentially also be designed in a way that it could be 3D printed together with the cup. The development effort for this would however exceed the scope and time of this project. Therefore, the alternative option by using the coffee grounds as a one way valve was explored by exploiting similarities as explained in subsection 2.2.1. The riser of a regular Bialetti was removed and coffee was brewed. Initially the concept seemed to work, however after about one minute the coffee drained rapidly, most likely due to an under pressure developing in the boiler as it cooled down. This quick experiment showed that this solution would not work. By exclusion, the approach of integrating the riser channel into the sidewall is chosen. This solution not only nicely leverages the potential of AM, but also solves issues regarding nesting and drinking from the cup.

**Splash Guard:**

An internal splash guard hood would interfere with the nesting of the two parts. Therefore, the approach of internally redirecting the flow of the coffee in the riser was further explored. The approach used nicely displays the methodology described in chapter 2. Using FDM 3D printing a small cap was manufactured which fits on the riser of a stock Bialetti, effectively adding an extension to it which redirects the flow of coffee downwards as can be seen in figure 4.4. Then a coffee was brewed, and the behaviour was observed. This quick experiment revealed that this approach produced no sputtering whatsoever. By keeping the same riser diameter in the new design, the flow of the liquid can be expected to have a similar velocity (no nozzle effects). Exploiting similarity therefore allows the use of a stock Bialetti to test this aspect of the new design and confirm its feasibility.

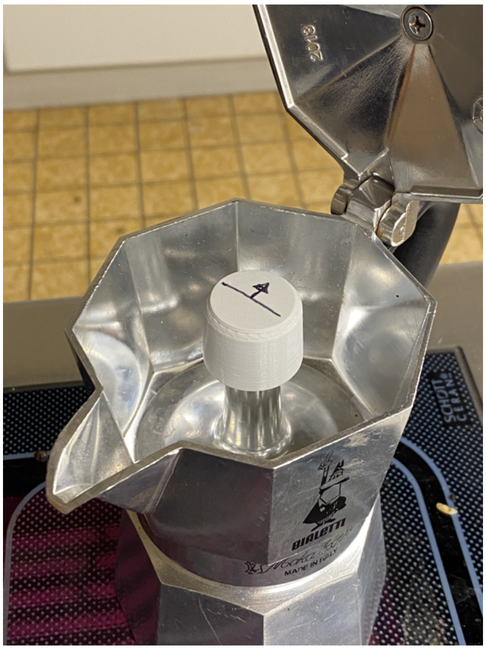



Figure 4.4: Experimental Verification of Splash Guard Concept

**Handle:**

In the case of the handle, many solutions seemed promising in terms of feasibility and practicality. However, the idea of using a material of low thermal conductivity to add a simple insulating element to the cup, which can directly be grabbed, certainly is best suited to the overall project goal of a lightweight and compact moka pot. Out of these options, using the thermal properties of titanium (which already is a promising material candidate due to its high strength to weight ratio) to produce a fully integrated handle which is printed completely self-supporting and does not require any post processing is the most tempting choice with regards to demonstrating the potential of metal additive manufacturing. The only question remaining is if the thermal conductivity is low enough to produce a contact area which can be grabbed with bare hands. An attempt was made to simulate the thermal behaviour of this solution, however as already described in section 3.2, the thermal situation in this system is fairly complex and producing accurate simulation results would be challenging, especially in the context of this short project. To at least get an approximate answer to this question, a thin walled titanium cup was filled with boiling hot water (which is roughly comparable to the cup in this design) and it was observed how far above the waterline the cup could be touched by hand. As this distance was approximately 10 mm, this approach seemed plausible, and a conductive path of this length (plus some additional margin) was used in later designs. Moving forward with this design does mean carrying a certain risk forward in the development process, something which is usually explicitly avoided. However, a backup plan is in place: In case the handle in the final design is too hot to touch, a small piece of leather could be added to it to further insulate it and make the design work as intended again.

**Valve Clearance:**

In a preliminary demonstration model, the possibility of a recessed valve was explored. However, it was quickly discovered that this solution occupies a significant amount of boiler volume (as a relatively large area needs to be recessed to allow installation of a safety valve). This in turn leads to a larger boiler size, which also leads to an enlarged cup size due to nesting. This cascading behaviour means that this approach produces a larger penalty in weight and volume than simply recessing a notch in the cup to allow for valve clearance. In the case of a conical shape, as described above, this recess can be further minimized as the cone geometry itself provides the clearance in the initial part of the stacking motion. Only as the two parts are moved closer together a recess is needed.

**Spout:**

As an integrated cup is used, a spout is not strictly required. In the prototype presented below, the valve clearance recess is shaped in a way that it doubles as a spout as well. A feature which is later deemed unnecessary and removed, as it was discovered that coffee could be poured cleanly without a spout in case it was to be shared among several cups.

**Wall Modifiers:**

Most of the proposed concepts to increase the heat transfer efficiency were discarded as they would have led to a significantly increased weight. The possibility of adding heat fins to the interior of the boiler was examined in more detail as this could be achieved with little extra weight. Analytical calculations using data obtained during the experiments described in chapter 3 suggest that adding heat fins makes sense if using aluminium which has a high thermal conductivity. In case of titanium, with its low thermal conductivity, heat flows mostly perpendicularly through the thin wall, and not significantly into protruding heat fins. This decision therefore remains open depending on material choice and on other design choices as well, such as for instance if the volume which would be occupied by heat fins is interfering with nesting. The approach of adapting the wall thickness to the local stress level will certainly be employed as it is highly beneficial and without any drawbacks.

## 4.4 First Full Scale Prototype

To conclude the conceptual design phase, the first fully integrated, full scale prototype was designed and manufactured using FDM 3D printing. It can be seen in figure 4.5. Below, some of its features and limitations are described. As already mentioned above, all functions which are described in the previous section are integrated into this design at full scale. The individual solutions are however just a first iteration and are subject to refinement. The entire design is already generally laid out for additive manufacturing, though not yet optimized for it (for instance, in terms of support requirements). It is also not yet dimensioned for the mechanical loads which will be exerted while brewing coffee. Finally, no particular attention has yet been paid to the visual design of the product.

Figure 4.5: Render of the First Full Scale Prototype

Since it is fully integrated, the produced prototype is however a great tool for functional testing: The handling and user experience does not differ between the FDM prototype and the final MAM version, and so things like the handle placement can be evaluated with this plastic-polymer model.[4] Other features like nesting can also be tried and tested.[5] Another important role of this prototype was to get feedback regarding its manufacturability from people with more experience in metal additive manufacturing. The physical model proved to be a great resource for communicating the design by being able to manipulate the model to show details. This first round of functional testing and the resulting lessons conclude the conceptual design phase.

[4]The author used the handles without issues. After several people tested the handling of the prototype, it was quickly discovered that the current placement might bring complications for people with smaller hands, as they cannot reach them without touching the cup. This highlights the importance of a physical model while testing.

[5]A small unforeseen clearance issue with the male thread was discovered this way.

# Chapter 5

# Optimisation

Starting from the full scale prototype presented at the end of the previous chapter, the following chapter explains the later iterations in design and the accompanying challenges due to the different optimisation problems at hand. Firstly, the domains of the optimisation process are described, followed by the results for each process.

## 5.1 Optimisation Challenges

There are three distinct challenges in this optimisation problem. Figure 5.1 shows the problem graphically. In order to refine the design, it has to be optimized structurally, in terms of product design and with regards to additive manufacturing. These challenges will be presented more detailed in the following:

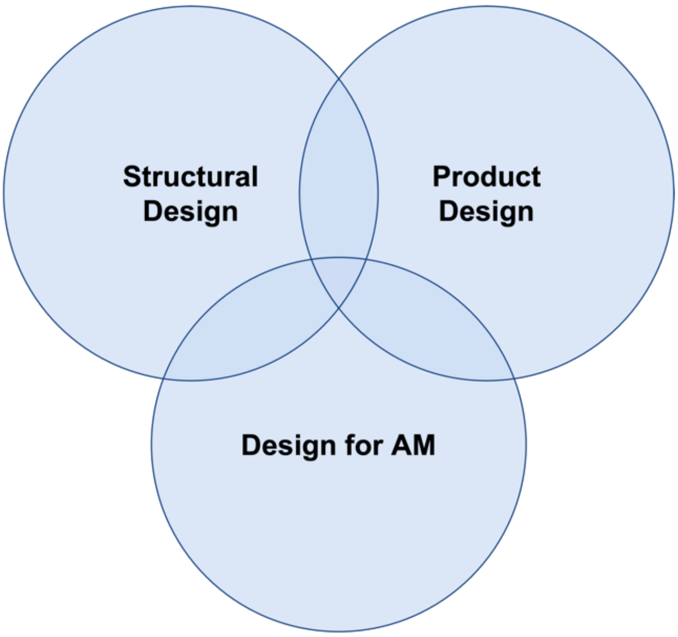



Figure 5.1: Optimisation Domains

### 5.1.1 Structural Design

The structural design optimisation is the most straightforward challenge of the three. The aim is to fulfil the primary goal of this project and make the moka pot as lightweight as possible. Simultaneously however, it also has to be able to bear the applied loads. The goal is therefore to design it as light as possible while being just strong enough. The material selection is also part of this process.

### 5.1.2 Product Design

Optimising the product design involves several aspects, all concerning how the user perceives the product. As a start, this involves the functionality of the product. This implies the improvement of the functions of the design, such as the nesting of the two parts inside of each other. The second element involves the user experience which is closely linked to how well the functions perform. Additionally, small details are enhanced or added. The aim is for the user to have a positive experience operating the product. The final topic of product design is concerned with its appearance. In this stage of the process, the goal includes improving the visual design as well, as it finally also adds to the user's enjoyment in operating the moka pot.

### 5.1.3 Design for Additive Manufacturing

Finally, the entire design has to be optimised for additive manufacturing. This involves two main aspects: Firstly, the parts have to be tweaked to improve printability. This includes selecting an appropriate printing orientation. It also implies adjusting the detailed design to minimise the required support structure, by making the geometry self-supporting (downslopes angled steeper than 45°, no unsupported overhangs). The previous two design challenges are true not only for MAM but also for other additive manufacturing technologies such as FDM. Specific to metal additive manufacturing is the fact that the thermal behaviour during printing has to be considered as well. The high energy input from the laser in SLM leads to a high temperature in the printed part. Care must therefore be taken to avoid heat accumulation and provision made for adequate part cooling. The high temperatures and thermal gradients result in high residual stresses within the part, which can lead to a number of ways in which the part can fail if it is not designed properly. The second main aspect of design for additive manufacturing comes once again from the goal of this project. Not only should the design comply with the specific rules of MAM, but it should also leverage the extended design freedom for creative solutions. There is no sense in 3D printing a part which could just as easily be cast or machined as well.

### 5.1.4 Finding a Compromise

Optimally, all elements of this design would be found in the intersection of the three domains visible in the center of figure 5.1. In reality however, often no such solution exists, and the designer has to prioritize one aspect and fulfil the other two as well as possible. The aim therefore is to come as close to the center as is feasible.

## 5.2 Structural Design

As already described in the previous section, the aim of structural optimisation is to make the existing design as light as possible while maintaining just enough strength to withstand the applied loads. In this section this process will be explained in more detail.

### 5.2.1 Optimising Weight

As the cup, and with it half of the design, is not under any particular mechanical load, the limiting factor regarding lightweight design is the manufacturing process itself. The global minimal wall thickness depends on printing performance, and in turn it influences the mechanical properties of the part. Going too thin might risk the part being delicate and getting damaged while in use or developing holes from pores or damage. If the minimum wall thickness is too thick, then the entire design will be unnecessarily heavy. Finding the right compromise is non-trivial. After getting feedback from people with more experience in design for metal additive manufacturing, as well as on the specific printer performance of the machine to be used, a minimum wall thickness of 0.5 mm was decided to be a good trade-off between sturdiness and weight.

### 5.2.2 Optimising Strength

At the current point the design is as light as it can be possibly manufactured. Now material is added back in areas of high stress until a stable point is reached. In order to analyse the mechanical response of the system, simulations using finite element methods (FEM) were used. To perform accurate calculations, it was important to clearly define the applied loads beforehand, which is going to be presented next:

**Applied Loads:**

The maximum pressure during regular operation has already been defined as 2.25 bar in the performance requirements presented in subsection 3.1.3. It has also been mentioned that in rare cases a blocked riser, caused by too finely ground coffee, can lead to an increased pressure within the boiler. For this reason, the safety valve is added, which limits the maximum pressure to $4 \pm 0.5$ bar according to its specifications.[1] The simulations were ran for both situations, applying both 2.25 and the maximum case of 4.5 bar.

Special attention has been placed on the locking element: It is not only subjected to the brewing pressure, but also an axial preload force applied by the compressed gasket. Determining this force therefore was a crucial step in simulating the mechanical response of the thread elements. Several attempts were made to characterize this gasket preload force by analysing its compressive behaviour or by correlating the compressive force to the torque applied when tightening the threads of a stock Bialetti. In the end both methods could not produce reliable results. Gasket compression is highly dependent on material and geometry. Thread pretension and tightening torque is only characterised for standardised bolts, which the Bialetti is not. A mechanical analysis based on thread pitch could be made, but that does not include the friction in the threads, which is expected to be significant. Finally, a solution to the problem was found: It once again exploits the similarity to the stock Bialetti due to the fact that the same gasket and boiler-gasket interface is used. First, the gasket compressive behaviour was recorded by observing how much a stock Bialetti was tightened angularly, and from this and the thread pitch the axial compression distance could be calculated. Then the gasket was placed on a flat surface, with the stock boiler arranged upside down on top of it. Next, weights were successively added to the boiler and the gasket displacement measured until the same displacement was observed as is produced in the thread of the

[1] A market review was performed in the hope of finding a high temperature gas valve of similar size and lower release pressure, to bring the maximum pressure closer to brewing pressure. Unfortunately, however, no such valve could be found.

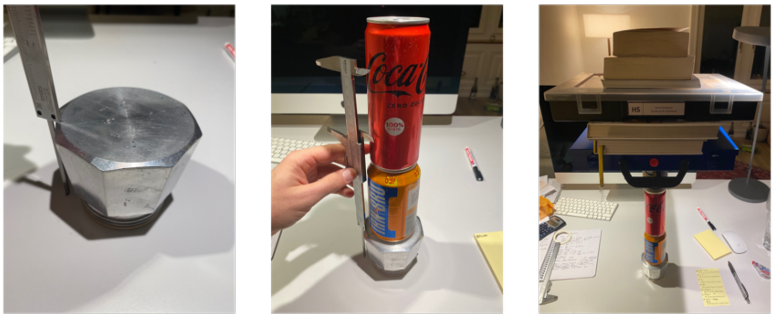


Figure 5.2: Gasket Compression Experiment - Home Office Version

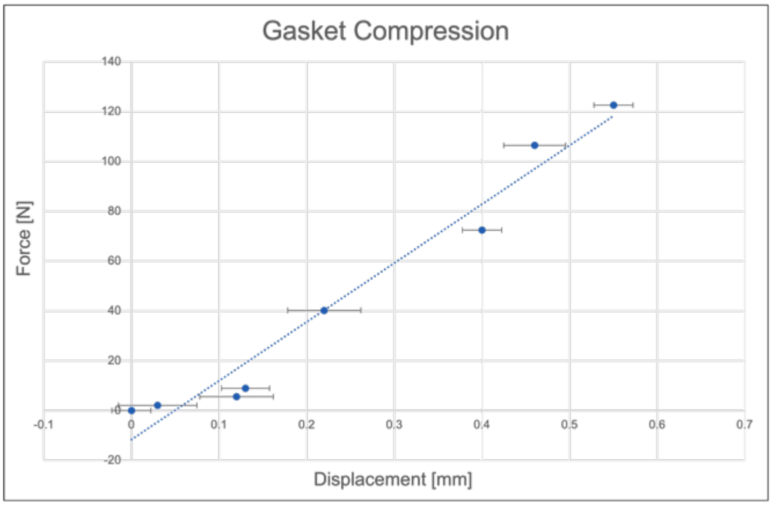



Figure 5.3: Gasket Compression Results - Force versus Displacement

Bialetti. This process can be seen in figure 5.2 This added weight represents the compressive force exerted on the gasket and in turn the gasket preload force on the locking mechanism. In numbers, a compression of 0.53 mm was observed in the Bialetti, and as one can see from the experimental results visible in figure 5.3, this corresponds to approximately 120 N of preload force. It can also be nicely seen that even with simple tools such as callipers and soda cans, a reasonably precise measurement can be obtained (The error bars in the graph indicate the variance calculated from five measurements which were performed for each added weight). This force is significant and therefore has to be applied to the locking element in the simulations.

**Simulations:**

Two static structural finite element simulations were performed in Ansys. The geometries were both meshed with a dynamic meshing strategy, with a more finely resolved mesh in areas of high stress which allows for accurate results, while still retaining a relatively low simulation cost. A mesh conversion study was performed in both cases to ensure reliable results. Both simulations were performed with aluminium and titanium, the two most promising material choices, using material properties for additively manufactured AlSi10Mg and Ti6Al4V found in the en-

gineering database within Ansys Workbench.[2] The materials chosen in Ansys do also contain properties for different temperatures. This feature was used, and the simulations were also performed at 100°C, the expected temperature in the bulk of the material while brewing coffee.
First, just the boiler was analysed with the aim of investigating the mechanical response of its profile under the applied pressure . Only the boiler was analysed to reduce computation effort. Then the wall profile was iteratively improved to add material were high stresses were observed. Redistributing and adding a small amount of material allowed to reduce stress concentrations and distribute the material load into the entire structure. An exemplary result of this effort can be seen in figure 5.4 which shows the stress distribution [3] for the aluminium design variation. The initial design is visible on the left, and the improved version on the right. The stress scales are not identical, as this is the only way to show the better material utilization in the later iteration. In this case the highest observed stresses went from 127 MPa to 40 MPa (2.25 bar brewing pressure, 100°C) by only adding 4 grams of weight (32 and 36g boiler weight). A similar optimisation was also performed for the titanium design variation which required a slightly different wall profile. Ultimately this process was however limited by the minimal wall thickness as described in subsection 5.2.1, which leads to the vertical parts of the profile being stiffer than required. The final goal of this analysis and optimisation, was to design the boiler in a way which is as light as possible while being able to withstand the maximum pressure of 4.5 bar defined in the paragraph above without exceeding the yield strength of the respective material, remaining completely in the elastic domain. This should also provide ample margin for fatigue performance in regular operation with 2.25 bar of applied pressure. This results in boiler designs (excluding the locking element) weighing 44.6g for titanium and 36.3 grams for aluminium.

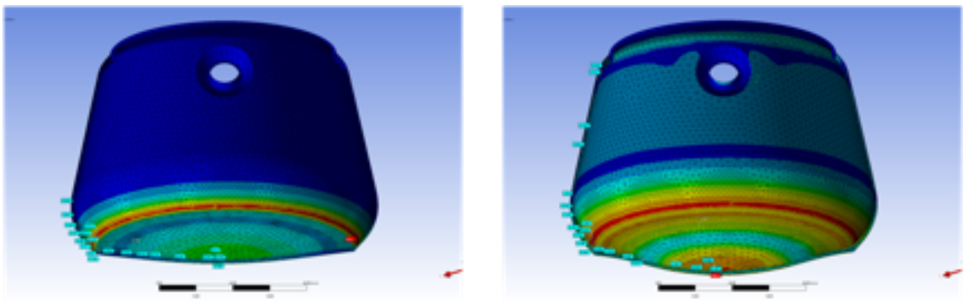


Figure 5.4: Boiler Wall Thickness Optimisation Results

A second simulation was then set up to also including the locking element as well as the optimised boiler structure. The gasket preload force is also included in this simulation. However, a problem arises from the connection of the male and female thread: At the load-transmitting edge of the contact surface a singularity occurs. Initially, the singularity was thought to be due to an inept design of this contact area, but further investigation revealed it to be an inherent problem of the FEM approach. As the two thread surfaces are not fully overlapping, each contact area experiences a sudden change from being backed by another part to not being backed at all, effectively crating a virtual sharp right angle corner. This geometrical contact

[2]Properties for additively manufactured materials are dependent on supplier as well as the manufacturing parameters. However, the properties present in Ansys are a good benchmark for what industrial SLM powder suppliers claim their products achieve.[2][3] The simulation results should however be treated with some care and an ample safety margin should be used.

[3]Equivalent von Mises stress

singularity therefore cannot be avoided at all, and so the precise stress at the edge of the threads cannot be evaluated using simulations. However, the general stress state of the thread element was used to improve its shape to reduce the overall stress. Additionally, the stresses surrounding the singularity reveal that the applied load most likely causes true stresses which exceed the yield strength of aluminium but are far below the yield strength of titanium.

### 5.2.3 Material Choice

The final aspect of the structural designing process is the material choice. As described in the previous section, up until now both aluminium and titanium have been considered, as both are promising candidates for lightweight design, and both are manufacturable using SLM as well. In chapter 4, when discussing the conceptual design, it has been established that a material with a low thermal conductivity is needed for the chosen concept for the handles. Additionally, this would insure that the upper lip of the cup would remain relatively cool, thereby allowing a user to drink directly from it. These thermal considerations therefore lead to titanium being chosen as the material for the cup.
As described in the previous section, for the boiler both aluminium and titanium could be used to produce a sufficiently stiff design, the former resulting in a slightly lighter system. However, by analysis of the locking element it seems that aluminium is most likely not strong enough for this application. The uncertainty introduced by the singularity could lead to the stress being overestimated though. In any case, titanium is chosen as well, leading to a slight weight penalty, but ensuring enough margin for the first metal print to be certainly functional. The performance of an aluminium version could be evaluated experimentally in the future.

## 5.3 Product Design

The improvements in product design are more subtle than the structural design decisions presented above. Most aspects have already been discussed in the conceptual design phase described in chapter 4, so now the realisation of a few exemplary elements will be presented.

### 5.3.1 Functionality

The functionality of the product has already reached a relatively high level in the first full scale prototype as seen in section 4.4, however some elements have been further improved. One example presented here is the nesting performance of the system which aims to fulfil the prime design goal of a compact system. Figure 5.5 shows a cross section view of the final design in this nested configuration with a minimal valve clearance recess visible on the left. A feature which was added at this point, were two small tabs inside of the cup which allow the boiler to be locked in place for transport by engaging its threads.
It can also be seen that the interior volume of the boiler is unobstructed, which allows for further improvement: The scope of this topic has been limited to the design optimisation of the moka pot, with no special consideration regarding the stove system which is also needed to brew a coffee. In the prime use case of thruhiking such a burner (usually a lightweight gas cannister stove) will be carried anyway. However, on shorter trips this gas stove and cannister are relatively heavy and bulky compared to the now optimised moka pot. In light of this project's effort a brief market research into even lighter ways of cooking has been performed. This resulted in the discovery of an ultralight alcohol syphon stove[4], also manufactured

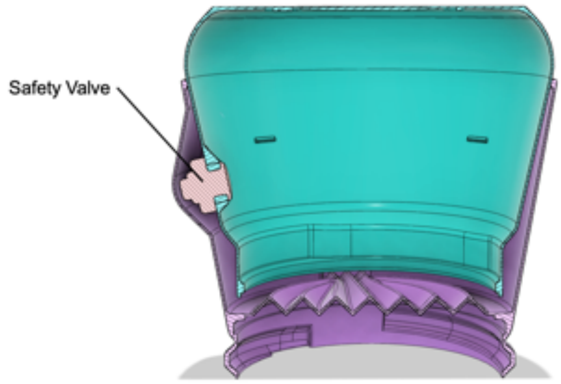



Figure 5.5: Nested Configuration

from titanium and weighing only 20 g. Coincidentally, its size allows it to be stored inside of the boiler, including a small custom made flexible pot stand which has been constructed out of thin titanium foil as well as a lighter. Furthermore, a small aluminium container has been purchased which fits inside of the powder basket and can carry enough fuel to brew a single coffee. Finally, an end cap has been produced using FDM 3D printing to cover the exposed end of the cup's threads while nested to prevent any remaining liquid to leak out into the backpack after use. This cap also has two additional functions, serving both as a convenient way to store a single portion of coffee grounds and as an insulating stove stand (the stove gets slightly warm during operation, which means it would melt the snow beneath it if used in winter). This setup effectively allows the user to carry everything which is needed to brew a coffee, including the stove, within the volume of the nested moka pot! It can be seen in figure 5.6 (from left to right: End cap with space for coffee grounds, fuel container, lighter, pot stand, alcohol stove and powder filter).


Figure 5.6: Compact Setup - Everything Stored in the Nested Moka Pot

### 5.3.2 User Experience

As already mentioned above, the user experience is obviously also dependent on all other aspects of the design, specifically the functional aspects presented above, and the visual design presented below. This section therefore primarily aims to reiterate that an emphasis has been placed on user experience design from the very beginning. FDM prototypes have been used extensively to verify the handling of the product and the manipulation of its features throughout all design stages. Feedback from functional test has been invaluable to designing a product which satisfies a user's needs. An example of this is for instance the feedback received for the handle placement in the first full scale prototype, as described in section 4.4. The new and improved handle design will be discussed in more detail in subsection 5.3.3 below. Designing for additive manufacturing opens up another possibility to improve user experience, as small details which guide the user can be added to the design at practically no additional cost. One example of this are the water fill level indicators that have been added to the boiler and serve to guide the user to add the right amount of water to the boiler. These small features can be seen as horizontal lines in figure 5.5 above.

### 5.3.3 Appearance

The final element of product design improvement is concerned with the visual appearance of the product. A side to side comparison between the two designs can be seen in figure 5.7. An attempt was made to find a uniform design language for the entire part, and to declutter its features into a more streamlined look. As can be seen in figure 5.5 which displays the nested configuration, one decision taken was to change the sidewall angle of the cup to be slightly steeper than the boiler. This was partially done to clear up the aesthetics of the cup to also only consist of a single, clean cone surface. Additionally, this change allows the riser to be designed as a channel integrated into the sidewall, thereby reducing its visual footprint on the outside of the cup (see figure 5.9 in the design for additive manufacturing section below for more details). Finally, the handles were redesigned to remain cooler, fit smaller hands and at the same time look sleeker, by placing them stacked on top of the riser, further decluttering the design. All these changes lead to a design which looks much more pleasing than the initial prototype.

Figure 5.7: Prototype (left) and Final Design (right)

## 5.4 Design for Additive Manufacturing

The final optimisation topic is driven by one of the key design requirements formulated in subsection 3.1.1, which states that the entire geometry should be optimised for additive manufacturing. Therefore, already in the conceptual design phase, careful attention has been paid to the printability of the parts (for instance the design considerations of the locking element, presented in section 4.3, are an example of this process). For this final design, another iteration of this optimisation has been performed which leads to the geometry presented now.

### 5.4.1 Minimising Support

One of the key challenges to overcome in design for additive manufacturing is to reduce the required support structure as much as possible or better yet to remove it altogether. This has almost been achieved with the final design, the entire boiler structure can be printed without using any support structure, and most of the cup as well. The only element which does require support is the bulkhead, the horizontal platform which separates the upper reservoir in the cup from its lower part which locks onto the boiler (grey part in the left image in figure 5.8). Initially, options of printing the cup in another orientation were explored, however it was discovered that printing it right side up results in the least amount of support required. In a next step this surface was then optimised to at least use a minimal amount of support, which additionally should also be easy to remove. The way this particular problem was solved was to use a triangular profile (center image in figure 5.8), which was swept to form a structure which allows coffee to flow freely towards the riser tubes. This profile was chosen because it only requires a single line of support at the base of each profile, with everything on top being self-supporting again. This results in the support profile visible in the right image in figure 5.8, which shows how this entire horizontal surface was printed with only six lines of support (The two circular supports surrounding them are necessary to print the flat flange for the gasket, no way of removing them was found). These six lines being isolated means that they are also much more easily removable than an entire surface completely covered by supports. The can simply be pried off with a pair of pliers. Due to the fact that the support interface surfaces are non-functional, even completely hidden from view after the gasket and sieve are installed, means that no further post processing is required. This is a great example where the extended design freedom of AM can be used to solve the particular design challenges of AM.

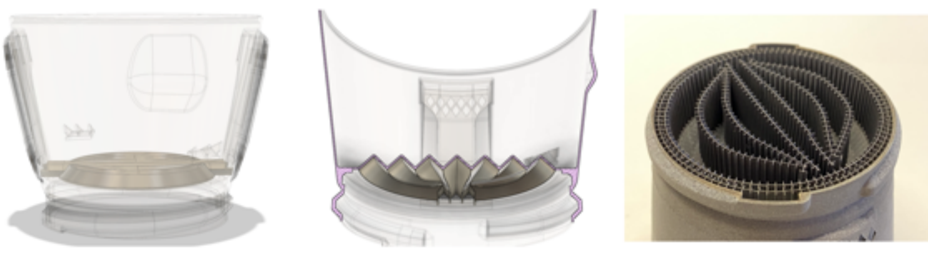


Figure 5.8: Bulkhead Design: An Example of Support-Minimising Design

### 5.4.2 Thermal Response

Another element of design for additive manufacturing are dealing with thermal effects during the manufacturing process. The heat applied to the part while printing can lead to deformations, which in turn can either violate dimensional constraints of the final part, or even cause issues during the printing process itself. An attempt was made to simulate the parts' behaviour while printing using the novel Ansys Additive simulation tool. Unfortunately, however these simulations currently have a very high computational cost, especially at this part size, resulting in simulations which took days to solve and couldn't produce accurate results due to necessarily coarse voxelisation. Due to the short time horizon of this project, these simulations were therefore not practically usable, and conventional design guidelines for MAM [5] had to be used to reduce the consequences of thermal effects.

### 5.4.3 Leveraging Potential of AM

As already mentioned in the previous section, the risers, including the splash guards which internally redirect the coffee downwards, have now been integrated into the sidewall, as visible in figure 5.9. The flow of the coffee from the bulkhead though the printed channel is highlighted with a white dashed arrow. Also visible are the two handles which tightly follow the curvature of the cup for a low profile solution. Due to only being connected at the very top and bottom, and the resulting long conductive path, they remain relatively cool while brewing coffee. Both design elements are printable without using any support, by using no surfaces angled shallower than 45 degrees. The horizontal internal channels all terminate in a triangular profile to satisfy this constraint. These are two examples of leveraging the potential of metal additive manufacturing to realise compact, lightweight and highly functional solutions which could not be manufactured in any other way.


Figure 5.9: Cross Sectional View of the Cup

# Chapter 6

# Manufacturing

Having concluded the design optimisation presented above, the design is ready for manufacturing. This process will now be presented, including the printing itself, the problems discovered, the proposed solutions to them and finally the required post processing and assembly of the parts.

## 6.1 Printing First Metal Prototype

The two parts were printed by laser powder bed fusion using a Sisma Mysint 100 machine loaded with Ti6Al4V powder. Due to the strong reactivity of titanium, an argon printing atmosphere had to be used (process chamber oxygen concentration below 1000ppm). The machine uses a 1070 nm fibre laser with a gaussian intensity distribution. The laser spot size is 55 µm, the maximum laser power 200 W. The geometries were sliced with a layer thickness of 30 µm. For every layer the contour was scanned first, proceeded by a bidirectional hatch scanning strategy. Line supports were used to support the required areas of the cup described in subsection 5.4.1. In order to account for base plate removal by electric discharge machining, or EDM, (cut width approximately 0.35 mm, but some uncertainty in precision), two different strategies were used. In case of the cup, where the bottom surface height is not critical, the entire surface was simply extended by 0.35 mm to account for the cutting kerf. The boiler's base thickness however is very thin in some areas (0.5 mm) and critical for the mechanical properties of the part. Therefore, the entire boiler was raised off the build plate by 0.8 mm and circular line supports were added to bridge the gap. This way the EDM cut can be placed in the supports, and their remains can simply be sanded back down accurately to the exact surface of the boiler. In hindsight this approach should not have been used due to issues with the part's thermal behaviour during printing, but more on this in section 6.2 below.
With these settings the print job was executed and took a total of twelve hours for both parts. The approximate cost, had the parts been ordered commercially, would have accounted to approximately 1500 CHF.[1] Despite encountering some problems, as described below, printing finished successfully.

[1] An online quote for the two parts was requested from Materialise OnSite, a commercial, low volume, SLM 3D printing provider.[6]

## 6.2 Discovered Printing Defects

Overall, both prints went relatively well, especially considering that both are first attempts at printing the designs from metal, something which often requires several iterations to reach a successful print execution. Nevertheless, both parts, despite best efforts to prevent any issues, each suffered from a problem characteristic of metal additive manufacturing.

### 6.2.1 Defect Description, Cause and Consequence

The observed defects, as well as their cause and consequence, will now be presented for both printed parts:

**Boiler:**

The print of the boiler finished seemingly without any issues, but after powder removal it became evident that the boiler had buckled, as can be seen in figure 6.1. From the buckling mode it can be concluded that the most likely reason is an in-plane compressive residual stress, most probably caused while already printed layers were cooling down. It seems that the printed part has simply been optimised slightly too far, resulting in a geometry which is able to bear the applied loads during coffee brewing, but not its own residual thermal stresses originating from manufacturing. Another potential reason could be caused by the layer wise manufacturing present in AM. While the entire part has a self-reinforcing shape, halfway during the printing process a more open, significantly less stiff profile is manufactured. The reinforcing properties only come into play once the locking element is printed. A secondary problem was discovered as well, which is that some of the support structure connecting the boiler's base to the build plate has cracked during printing, thereby allowing the part to bend more easily. This also resulted in slight warping of the boiler's bottom surface. Luckily the side walls are not warped sufficiently to interfere with nesting the two parts within each other (also thanks to the clearance introduced, as described in subsection 5.3.3). However, as the locking element is also partially warped, the threads are seizing after about one third of the engagement in the as printed shape.

Figure 6.1: Buckling Visible in Boiler Print

**Cup:**

The print of the cup suffered from a more dramatic defect. During the printing of the initial layers of the support minimising bulkhead profile discussed in subsection 5.4.1, a small piece of the printed geometry was observed to be warping upwards. It then managed to break away from its support and stuck up vertically. This sharp little piece then repeatedly collided with the rubber powder recoating blade, eventually damaging it. This small gash in the recoater in turn led to an uneven powder distribution, not depositing any powder where the recoating blade was missing, and thereby starting to create a small hole in the part in this location. Luckily this defect was caught in time, and the print stopped. The warped part was then manually removed, the recoating blade replaced, and powder refilled and relevelled. This allowed to print to be continued successfully to completion without any remaining consequences. The reason for this defect also comes from over-optimisation, this time in the minimisation of supports. Figure 6.2 shows the cross-sectional view of the cup on the left, and a sliced view on the right which corresponds approximately to the layer of the print where the failure occurred. In order to reduce the amount of printed material and improve the flow of the coffee, the bulkhead profile was swept upwards towards the risers, resulting in a convex bottom edge. In slicing this part, initially only a short, sharp, isolated cantilevered element is printed on the single support line beneath it. Heat accumulation, excessive warping and finally a blade collision in the tips of these profiles (failure area indicated with red circle) are almost unavoidable in this scenario and represent a crucial oversight in following design rules for metal additive manufacturing. Fortunately, the part was saved by a quick reaction during printing, and all other aspects of it printed without any problems.

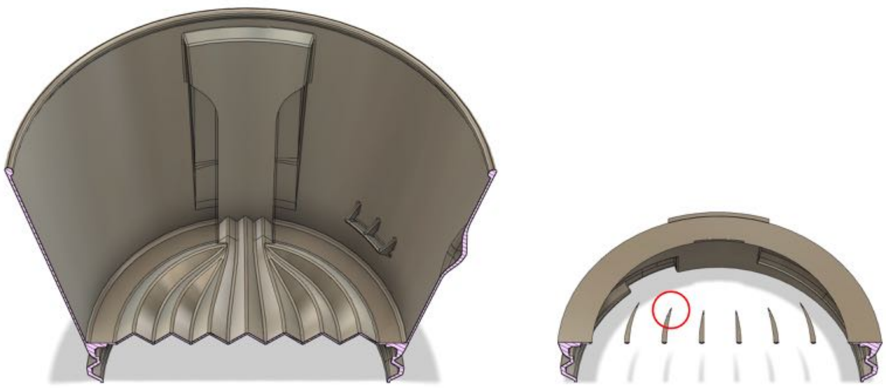


Figure 6.2: Warping Location in Full and Sliced Model

### 6.2.2 Proposed Design Improvement

In the following, design improvements with the aim of preventing both defects described above are presented:

**Boiler:**

Several changes to the boiler model and printing approach have been made to correct the warping issue at hand. Before going into details, one important point has to be stated: Some degree of warping must be expected in these thin-walled parts, and the design also accounts for that by providing clearance in non-functional areas. It is only important to completely remove the warping in the functional surfaces of the locking element. Some warping, though hopefully significantly less, can be tolerated in the sidewall. The first change has been performed in the CAM setup of the print job: Instead of suspending the parts on supports (which partially failed), the part is also extended downwards by 0.4 mm. Thereby allotting just enough margin to produce a slightly oversized part after EDM baseplate removal. This does result in a small weight penalty, but in turn it should allow for increased cooling performance and a significantly stiffer part during the printing process. The two other improvements have been made to the part's geometry and can be seen in figure 6.3: First, small ribs have been added to the upper side wall, aiming to stiffen it during the printing process and hopefully resulting in a stable, stiff base to print the locking element on top. Secondly, the locking element wall thickness has been doubled to make it much stiffer should and better suited to resist any residual stresses. Both measures only add a small weight penalty to the entire system (ribs: +0.7 g, lock: +1.5g). Hopefully this combination of countermeasures are sufficient to prevent warping in future prints, otherwise further reinforcement would have to be added to the upper side wall.

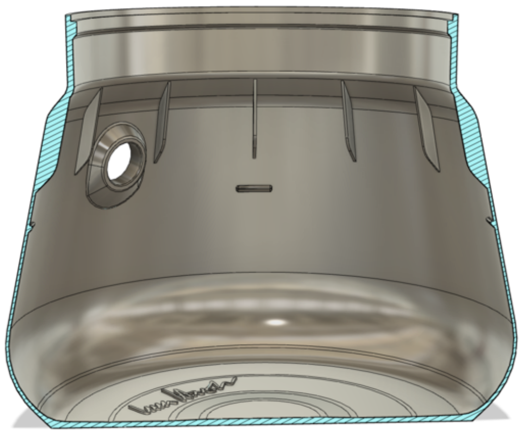


Figure 6.3: Stiffened Boiler Design

**Cup:**

Due to the fact that the design error in the bulkhead profile is much more obvious, its solution luckily is more trivial as well (and should have been implemented from the beginning). It can be seen in figure 6.4: The base of each profile is simply extended downwards, so that the entire profile starts on a single plane (added extension marked by red arrow in the left image in figure 6.4, see figure 5.8 for old profile). This leads to a closed profile already in the first printed layer of the bulkhead (visible in the right image in figure 6.4). The closed nature prevents sharp ends which could warp up excessively and cause a blade collision. In theory the entire length of the bulkhead profile could still warp slightly, but it would have to break free from an entire line of support beneath it, and if it were to warp, it is expected to just buckle upwards slightly in the center, as both ends are pinned. In order to further reduce the chances of any future printing problems, the model will be printed with the recoating direction aligned with the direction of the bulkhead profiles. In case of any warping, the soft rubber lip of the recoater should be sufficient to comply to the expected smooth buckled shape without being damaged or obstructing clean powder recoating. The entire change is expected to only add 0.7 g of weight to the system.

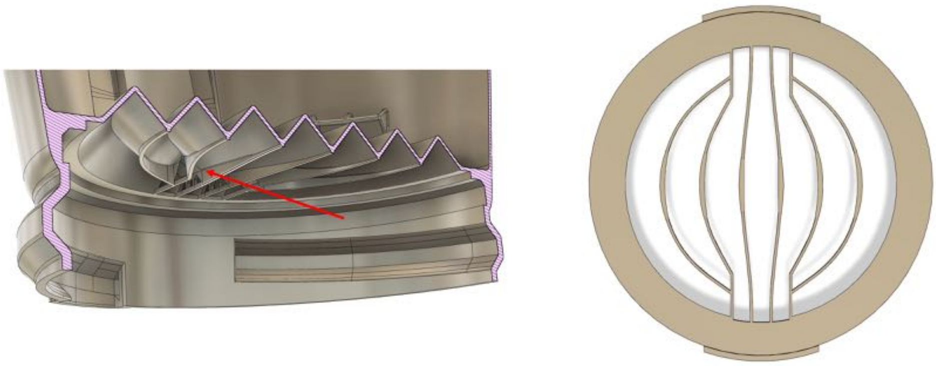


Figure 6.4: Improved Bulkhead Design - Detail View and Sliced Model

## 6.3 Post Processing and Assembly

The post processing of this part has been reduced to a minimum by design. The few steps which still are required as well as the final assembly are described below. As already mentioned above, the parts are separated from their build plate by means of wire EDM, an automated process which takes about one hour per part. Next, the hole for the safety valve is drilled out and an M9 x 0.75 metric thread is tapped. These steps are proceeded by the three processes visible in figure 6.5: First the warped boiler is bent back into a more circular shape to allow operation of the locking mechanism, a step which should not be necessary in future prints due to the design improvements described above. As a next step, the eight lines of support are removed manually. A process which takes only a few moments and a pair of pliers to break them out, due to their well thought out design. Finally, some residual support material has to be removed from the flange against which the gasket forms a seal, a process which again only takes a few minutes. The support interface of the bulkhead does not require any further post processing, as it is not a functional surface. Furthermore, the bottom of the boiler is sanded flush using a drum sander. In total the post processing took about two hours of machine time (EDM) and about one hour of manual labour (reduced to 30 minutes without needing to correct the warping of the boiler).

Figure 6.5: The Three Manual Post Processing Steps: "Unwarping", Support Removal and Grinding

After completing the post processing, the finished parts can now be assembled. Additionally to the two printed parts, the following readily available parts are required:

- A Bialetti 3 cup powder basket
- A Bialetti 3 cup gasket
- A Bialetti 3 cup sieve
- A Bialetti pressure safety valve[2]

The gasket and the sieve can then simply be installed manually, with the gasket locking the sieve in place, just like in an original Bialetti. The powder basket can just be loosely placed in the top of the boiler. The safety valve has to be installed using a food-safe, pressure-proof, high-temperature thread sealant[3] to ensure no that no leaking occurs. With these parts installed, assembly is complete.

[2]The valve either has to be reused from a stock Bialetti or bought from an aftermarket supplier. Bialetti does not offer replacement valves.

[3]Loxeal 58-11 was used in this project, as it fulfils all three requirements.

# Chapter 7

# Evaluation

In this chapter the final design will be presented. Its weight and size will be analysed and compared to an original Bialetti and finally its function as a moka pot tested.

## 7.1 Thrubrew

The final system, or "Thrubrew" as a reference to thruhiking and coffee brewing, is going to be presented in this section: The entire system, including all the added stock Bialetti parts as explained in section 6.3 above, can be seen in figure 7.1 in both the brewing and the nested configuration. The complete moka pot weighs only 142 grams. In its nested configuration it only uses a volume of about 0.4 L of backpack space. Furthermore, an ultralight alcohol stove, a pot stand, fuel, a lighter, as well as a single serving size of coffee can be stored inside of it. The upper reservoir also doubles as a cup, thereby eliminating another piece of gear required, effectively making this product a self-contained, compact and lightweight solution to enjoying a cup of freshly brewed coffee in the great outdoors.

Figure 7.1: Thrubrew in Brewing and Nested Configuration

## 7.2 Numerical Comparison to a Bialetti

In this section the numerical performance of Thrubrew will be compared with the original 3 cup Bialetti which has served as a baseline for the entire development process. In terms of weight, both coffee brewers will be compared in two ways: The primary comparison is between the brewers themselves, including all necessary parts, such as the powder basket. In a second step the entire coffee brewing system, this time including a stove and fuel will be compared. This comparison serves to exemplify the overarching approach to an ultralight setup. However, the stock Bialetti could obviously also be used with the ultralight alcohol stove presented in subsection 5.3.1, instead of using the traditional lightweight gas stove. Finally, the stowed volume of both setups will be compared as a measure for compactness. The results of these comparisons are very clear. Thrubrew is approximately seventy percent lighter than a conventional setup, and almost ninety percent more compact! Table 7.1 contains the exact numerical values.

Table 7.1: Numerical Comparison Between Thrubrew and a Bialetti

| Property | Unit | Bialetti | Thrubrew | Decrease |
|---|---|---|---|---|
| Brewer Weight | g | 465 | 143 | 69 % |
| Stove Weight | g | 276 | 61 | 78 % |
| Total Weight | g | 741 | 204 | 72 % |
| Stowed Volume | L | 3.0 | 0.4 | 87 % |

## 7.3 Functional Testing

Evaluating the functional performance of Thrubrew was trivial: The boiler was filled with water, the powder basket filled with coffee grounds and inserted, the two halves connected to each other, and the entire brewer placed on a heat source. Then, after a few minutes, delicious freshly brewed coffee started gently flowing out of both risers. The produced coffee is exactly as expected, the locking element functions nicely without leaking, and both it and the boiler seem to be mechanically sound without displaying any issues. Furthermore, no coffee is sputtered out of the cup while brewing, thanks to the integrated fluid flow redirection. As can be seen from the left image in figure 7.2, the handles also work just as intended, remaining cool enough to allow the user to grab Thrubrew immediately after brewing coffee. Finally, the coffee can be easily and safely consumed directly from the integrated cup.

As can be seen in the right image in figure 7.2, Thrubrew has since also been field tested on several ski mountaineering trips and the entire set up, including the ultralight alcohol stove, performs flawlessly.

Figure 7.2: Functional Testing of Thrubrew

# Chapter 8

# Conclusion

The development of an ultralight moka pot has been described in this paper. In the previous chapter 7, Thrubrew's performance has been analysed in detail. It is safe to say that by decreasing the system's weight by seventy percent, and its stowed volume by almost ninety percent, the project goal of designing a lightweight and compact coffee brewing system has been achieved. Additionally, an agile design methodology was purposely chosen and followed to develop a design optimised for metal additive manufacturing, with the secondary goal of manufacturing a functional model with the first full scale print. Despite some challenges, presented in section 6.2, this goal has been achieved as well. The model presented in the previous chapter is indeed the very first print. One small task remaining at this point is printing and evaluating the improved design presented in subsection 6.2.2.

# Bibliography


[1] "Bialetti CT Scan". [Online]. Available: https://en.wikipedia.org/wiki/File:Espressokanne.ogg, Accessed: 21.02.2022.

[2] "Ti6Al4V Powder Data Sheet - SLM Solutions". [Online]. Available: https://www.slm-solutions.com/fileadmin/Content/Powder/MDS/MDS_Ti-Alloy_Ti6Al4V__ELI_0719_EN.pdf, Accessed: 28.02.2022.

[3] "AlSi10Mg Powder Data Sheet - SLM Solutions". [Online]. Available: https://www.slm-solutions.com/fileadmin/Content/Powder/MDS/MDS_Al-Alloy_AlSi10Mg_0221.pdf, Accessed: 28.02.2022.

[4] "Toaks Titanium Alcohol Siphon Stove". [Online]. Available: https://www.toaksoutdoor.com/products/stv-01?variant=31415425990, Accessed: 28.02.2022.

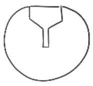
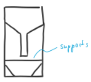
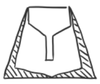
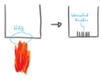
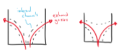
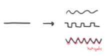
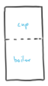
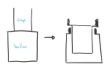
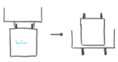
[5] C. Klahn and M. Meboldt, *Entwicklung und Konstruktion für die Additive Fertigung*. Vogel Communications Group GmbH, 2021.

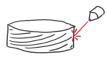
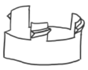
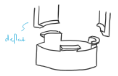
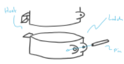
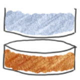
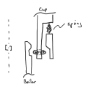
[6] "Materialise OnSite". [Online]. Available: https://www.materialise.com/en/manufacturing/materialise-onsite, Accessed: 28.02.2022.

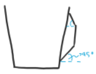
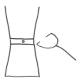
# Appendix A

# Conceptual Design - Solution Overview and Analysis

The following table shows a detailed explanation and analysis of each proposed solution. Every solution is first described in detail, including benefits and drawbacks. The analysis follows a morphological box approach, rating each solution idea by applicable criteria in order to select the most promising ideas for further development. Most elements are explained in more detail in chapter 4.

| Concept Overview | | | | Red elements mark killing criteria | Yellow Elements are favourites | Rated relativ to each other from 1 (worst) to 3 (best) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Illustration** | **Name** | **Pro** | **Con** | **Notes** | **Rating** | **Pressure** | **Weight** | **Manufacturability** | **Nesting** | **Functionality for User** | **Simplicity (Elegant Design)** | **Sum** |
| **Boiler Shape** | | | | | **Boiler Shape** | | | | | | | |
|  | Cylindrical | optimal pressure-wise | unstable (rolls over)<br>top overhang hard to print<br>large top volume is inefficient (large gas pocket)<br>not very compact | | Cylindrical | 3 | | 1 | 1 | 1 | | 6 |
|  | Rounded Cone | stable<br>easier to print (especially if initial overhang is champferd)<br>nesting possible if solid angle is constant | less optimal for pressure | | Rounded Cone | 2 | | 3 | 3 | 3 | | 11 |
|  | Rounded Cylinder | closesly represents pressure tank<br>stackable | stackable, but only if cup is wider (balance worse)<br>top overhang hard to print<br>large top volume could provide problems while extracting coffee (compressible gas pocket) | | Rounded Cylinder | 2 | | 2 | 2 | 3 | | 9 |
| <br> | Reinforced Cylinder | easily stackable<br>main shape easy to print | hard to optimize for pressure<br>hard corners inherently stress-risers | Supports could be added to different design as well | Reinforced Cylinder | 1 | | 2 | 2 | 3 | | 8 |
| **Shape Irrelevant Modifiers** | | | | | **Shape Modifiers** | **Pressure** | **Manufacturability** | **Efficiency of Measure** | **Weight Penatly (3 smallest)** | | **Simplicity (Elegant Design)** | |
|  | Inhomogenous Thickness | use AM-Freedom<br>freedom of boiler shape (can be applied to any geometry) | needs more material than optimal shape (weight penalty) | could be used to further optimise any geometry | Inhomogenous Thickness | 2 | 3 | 3 | 3 | | 2 | 13 |
| <br> | Heatfins | cool heat affected zone (HAZ)<br>heat water quicker | TI is a bad conductor (limited use) | TI is a bad conductor: | Heatfins | 1 | 3 | 1 | 2 | | 2 | 9 |
|  | Internal Channels | increase surface area in hottest zone (less thermal load per material)<br>use hot gasses more efficiently to heat warmer water | loose internal volume (increased total volume/weight)<br>manufacturibility | Heat transfer is only efficient through as little TI as possible! (directly from air, through thin TI-wall, into water) Heat transfer over long TI-distances not efficient (water, through TI into heatfin, into water) | Internal Channels | 2 | 1 | 2 | 1 | | 3 | 9 |
|  | Increased Surface Area | increase surface area in hot zones (cool TI/heat water)<br>use AM potential | certain geometries could lead to localized hotspots<br>manufacturability | | Increased Surface Area | 1 | 2 | 2 | 2 | | 2 | 9 |
| **Cup Shape** | | | | | **Cup Shape** | **Pressure** | **Weight** | **Manufacturability** | **Nesting** | **Functionality for User** | **Simplicity (Elegant Design)** | **Sum** |
| <br> | External Cup | multifunctional cup | harder to integrate functions<br>not necessarily very compact<br>more cumbersome, less user friendly | riser could be flexible for stowability | External Cup | | 1 | | 1 | 1 | | 3 |
| <br> | Integrated Cup | stable & compact<br>full design freedom in all components | | | Integrated Cup | | 3 | | 3 | 3 | | 9 |
| <br> | Hybrid - Retained external cup | stable<br>multifunctional cup | harder to integrate functions<br>not necessarily very compact<br>more cumbersome, less user friendly | | Hybrid - Retained external cup | | 1 | | 1 | 2 | | 4 |
| **Nesting** | | | | | **Nesting** | **Pressure** | **Weight** | **Manufacturability** | **Nesting** | **Functionality for User** | **Simplicity (Elegant Design)** | **Sum** |
|  | Cup in Boiler | | boilder opening constrained by basket (high & narrow cup)<br>boiler bottom diameter constrained by stove interface (wide and flat boiler)<br>--> inefficient nesting | initial idea: flip threads and screw cup in upside down for stowing. BUT: seal is in the way! | Cup in Boiler | | | | 1 | | | 1 |
|  | Boiler in Cup | design freedom of cup can be used to facilitate optimal nesting | lock is exposed (damage?)<br>Vboiler>Ccup (3:2), leads to boilkder sticking out of cup | | Boiler in Cup | | | | 3 | | | 3 |
| **Lock** | | | | | **Lock** | **Compliance** | **Locking** | **Manufacturability** | **Weight** | **Reliabiity** | **Simplicity (Elegant** | **Sum** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Machined Threads | certainly works!<br>Easy to print<br>compliance for o-ring compression (needed for pressure tight seal)<br>enough friction to lock | requires post-machining | | Machined Threads | 3 | 2 | 2 | 3 | 3 | 1 | 14 |
|  | 3D printed conventional threads | functionally works<br>more elegant (no post-processing)<br>compliance&locking | manufacturable?<br>Not very creative | | 3D printed conventional threads | 3 | 2 | 2 | 3 | 2 | 1 | 13 |
|  | oversized 3D printed thread | should probably work<br>easier to 3d print<br>compliance | requires more space/weight<br>locking not guaranteed (steeper threads) | surface roughness could assist in locking | oversized 3D printed thread | 3 | 1 | 2 | 2 | 2 | 3 | 13 |
|  | Partial oversized printed threads | lighter weight than above<br>compliance | **no area to seal!!**<br>Locking? | | Partial oversized printed threads | | | | | | | |
|  | Snap fit & Twist to release | none in comparison to above | TI elastic enough<br>**no area to seal**<br>locking? | | Snap fit & Twist to release | | | | | | | |
|  | Hook and Latch | could relatively easily be printed (except hook)<br>certainly locking | more comlicated<br>no compliance | | Hook and Latch | 1 | 3 | 1 | 1 | 1 | 1 | 8 |
|  | Bayonet Style Thread | simple mechanism | unsupported overhangs: not printable like this<br>compliance&locking<br>high stress on pin | | Bayonet Style Thread | | | | | | | |
|  | Geka-Style Threaded Bayonett | | requires softer oring<br>no need for genderless coupling<br>overcomplicated | | Geka-Style Threaded Bayonett | 2 | 2 | 1 | 1 | 2 | 1 | 9 |
|  | Espresso machine type Bayonett | working design (espresso machine)<br>pressure prove (orings exist)<br>compliance | locking with AM-part? | could be adapted for AM by printing a thin shell which is champferd in and out to form thread | Espresso machine type Bayonett | 3 | 1 | 2 | 2 | 2 | 3 | 13 |
|  | Self sealing through inhomogenous thermal expansion | very elegant solution | **reliability**<br>thermal expansion coefficient of available materials too similar (stainless 14-17 um/C, TI 9um/C)<br>deltaTmax = 80°C<br>deltaLmax = 5*8=40um=0.04mm | | Self sealing through inhomogenous thermal expansion | | | | | | | |
|  | Quick Connect Coupling Style | Very easy locking & unlocking (cup could be detached after brewing for drinking)<br>easy to print or post machine (drill holes) | complex, moving parts, springs, ball bearings<br>realiability? | | Quick Connect Coupling Style | 1 | 3 | 1 | 1 | 1 | 1 | 8 |
| **Riser** | | | | | **Riser** | **Weight** | **Manufacturability** | **Nesting** | **Functionality for User** | **Reliability** | **Simplicity (Elegant Design)** | **Sum** |
|  | Internal, stock | could probably be best adapted for AM | obstructs nesting | no obvious benefits except for perhaps most direct coffee routing (not anticipated to be critical) | Internal, stock | 1 | 2 | 1 | 1 | 3 | 1 | 9 |
|  | Internal, Side | more space efficient<br>drinking unrestricted | still obstructs nesting to some degree | | Internal, Side | 1 | 1 | 2 | 2 | 3 | 2 | 11 |
|  | External, printed | internal volume of cup freed, good for nesting and drinking | more difficult to design for AM (overhangs after lock) | | External, printed | 1 | 1 | 3 | 3 | 3 | 2 | 13 |
|  | External, added part | internal volume of cup freed, good for nesting and drinking | easier to manufacture, but interstage is still hard<br>added part, less practical | | External, added part | 1 | 2 | 2 | 1 | 3 | 1 | 10 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | No riser, check valve at cup bottom | no interfearance of riser at all, direct coffee routing in interstage<br>easy to manufacture in AM | reliability of valve/ ease of use? | little overpressure problematic? Leaking for weak spring? | No riser, check valve at cup bottom | 2 | 1 | 3 | 3 | 1 | 2 | 12 |
|  | No riser, coffee grounds as one way valve | cleanest design<br>easy to manufacture | leaking? Coffee powder in cup? | check experimentally<br>--> doesn't work | No riser, coffee grounds as one way valve | 3 | 3 | 3 | 2 | 1 | 3 | 15 |
| **Handle** | | | | | **Handle** | **Weight** | **Manufacturability** | **Compactness** | **Functionality for User** | | **Simplicity (Elegant Design)** | **Sum** |
|  | Plastic | | needs to be away from heat -->cantilevered like original<br>strength? Weight?<br>Bulky | | Plastic | 2 | 2 | 1 | 3 | | 1 | 9 |
|  | TI, printed hinge | integrated, use of AM-freedom | printability? Strength? Stowability | FDM 3D printed hinge possible, but MAM? complex? | TI, printed | 2 | 2 | 2 | 3 | | 2 | 11 |
|  | TI, wire | proven design (all outdoor cooksets use this design)<br>lightweight, sturdy, foldable<br>print attachment points | manufacturing challenge of bending custom handles?<br>Depending on solid angle, folding could become tricky | Salvage from cup? | TI, wire | 2 | 2 | 3 | 3 | | 2 | 12 |
|  | Insulating Pads as Handle (Wood, Leather) | easy to manufacture and integrate<br>visual design | | | Insulating Pads as Handle (Wood, Leather) | 2 | 3 | 3 | 3 | | 3 | 14 |
|  | TI Heat Break as Handle | relatively easy to print<br>great use of TI&AM | | | TI Heat Break as Handle | 3 | 3 | 3 | 3 | | 3 | 15 |
|  | Handle acting as a lock | integration of functionality | practicality<br>stowability<br>reliability<br>handling | | Handle acting as a lock | 1 | 1 | 1 | 2 | | 2 | 7 |
|  | External (Stowed) Grippers (like old camping pots) | easy to manufacture or even buy | not very user friendly or elegant | | External (Stowed) Grippers (like old camping pots) | 1 | 2 | 1 | 1 | | 1 | 6 |
| **Safety Valve Nesting Clearance** | | | | | **Safety Valve** | **Pressure** | **Weight** | **Manufacturability** | **Nesting** | **Functionality for User** | **Simplicity (Elegant Design)** | **Sum** |
|  | Recessed | no interference with the rest of the design<br>showcase for AM freedom | uses up internal volume of boiler --> boiler size increase --> cup size increase<br>big mass penalty<br>cumbersome | | Recessed | 1 | 1 | 2 | 2 | 1 | 1 | 8 |
|  | Normal, Notch in Cup | boiler design not affected<br>design freedom of cup used<br>functionality integrated (spout)<br>uses very little extra material | | notch could be L-shaped to lock the boiler while stowing! | Normal, Notch in Cup | 3 | 2 | 3 | 3 | 2 | 2 | 15 |
| **Spout** | | | | | **Spout** | **Weight** | **Manufacturability** | **Compactness** | **Functionality for User** | | **Simplicity (Elegant Design)** | **Sum** |
|  | Small | little extra weight, simple to use | slightly larger formfactor<br>spout needed? | | Small | 2 | 2 | 2 | 2 | | 1 | 9 |
|  | Big, Notch for valve | multifunctional, makes space for valve | more weight, volume used<br>spout needed? | L shaped to lock boiler when stowed? | Big, Notch for valve | 1 | 2 | 1 | 3 | | 3 | 10 |
|  | None | most elegant | valve? | | None | 3 | 3 | 3 | 1 | | 1 | 11 |