Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

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Low-cost tooling concepts for customized tube bending processes using hybrid design and additive manufacturing

Master's thesis in MTPROD
Supervisor: Jun Ma
Co-supervisor: Sigmund A. Tronvoll
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DEPARTMENT OF MECHANICAL AND
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Abstract

The focus of this thesis is on the flexible bending process for manufacturing customized bent components and structures. The metal forming process takes in an aluminum tubular profile and bends it into the desired shape with the desired dimensions. End quality and strength will be variable and depend on the application of the tubular product, and whether it is meant for a hard operational environment or a lighter field where parts are more replaceable. Therefore, the premise is a tooling part that is present during the bending process as a support for an optimal tubular profile, to ensure that the right quality and properties for the finished product are obtained. These types of support tooling are placed inside the profile, at the exact location of the bending point, to ensure an even cross-section and a tube product that is without wrinkles and excessive defects. Support tooling like these require high dimensional accuracy and durability and are therefore expensive to manufacture and normally require a long lead time and strong materials.

Research has been extensively and thoroughly conducted on metal mandrels and how they are able to significantly toughen and strengthen the quality and properties of a post-processed part. However, further development in the field of additive manufacturing and the combination of methods to the process has subsided. Therefore, this research has gone into the conceptual design, prototyping, development, and testing of tools by additive manufacturing with one specific low-cost material; PLA. During the experimental testing stage, multiple specimens have been tested, qualitatively analyzed, and measured to gain experience with the produced tooling and to see how well rigid tooling, as well as flexible tooling, performs compared to conventional tooling. The multiple tests per specimen ensure dimensional accuracy and that tests are repeatable and of use to draw conclusions.

The focus on more customized production processes and parts that can quickly be changed and tailored to cater to different needs has never been higher. Plans and processes must therefore be more efficiently evolved to meet the demand of the market and customer. This can be achieved in a cost-efficient way by combining AM and metal forming, to produce quality tooling components.

Keywords: rotary draw bending, flexible mandrel, additive manufacturing, product flexibility, PLA.

Sammendrag

Denne oppgavens fokus vil være på den fleksible bøyeprosessen som tar plass i en rørbøyingsmaskin. Denne forminsprosessen tar inn en aluminiumsrør og bøyer det til den ønskede formen, med de rette dimensjonene. Det endelige resultatet av produktet vil variere og være avhengig av hvilke applikasjonsområde røret skal ha, samt hvilket område rørene skal være plassert i med tanke på det operasjonelle miljøet. Premisset for å lage en optimal rørprofil som har de beste kvalitetene og egenskapene, er derfor å ha en støtteverktøy under bøyeprosessen. Denne typen støtteverktøy, eller dor, er plassert inne i røret, på det eksakte stedet bøyingen tar plass. Med en slik støtte vil tverrsnittet på det bøyde røret til en større grad holde sin ekte form, samt senke den overflødige oppsamlingen av matriale, som igjen skaper rynkninger på røret. Slike støtteverktøy krever høy nøyaktighet rundt mål og dimensjoner, samt at de må være svært robuste. Dette resulterer i at de er svært kostbare både når det gjelder pris og ressurser brukt under produksjonsprosessen.

Det er gjort mye forskning på metalstøttesverktøy og hvordan de er i stand til å betraktelig styrke både kvaliteten og egenskapene til en ferdigbøyd rørprofil. Imidlertid har ikke utviklingen innenfor kombinasjonen av additiv tilvirkning og konvensjonell metallforming vært like stor. Derfor har denne oppgaven gått ut på å designe, printe, videreutvikle og teste støtteverktøy ved hjelp av additiv tilvirkning. I løpet av oppgaven har de produserte produktene blitt testet og målt for å få ett bilde av hvor godt de yter sammenlignet med støtteverktøy produsert på den konvensjonelle måte. En rekke tester per rør har blitt gjennomført for å sikre den dimensjonelle nøyaktigheten og for å forsikre at testene er repeterbare og mulige å bruke til å trekke visse konklusjoner.

Fokuset på en mer tilpassningsdyktig produksjonsprosess, og deler som er mulige å brukes på ett større område enn ett spesifikt bruksområde, er svært stort. Prosesser må derfor utvikles slik at det møter disse kravene til både markedet og kunder. Dette kan gjennomføres på en kostnadseffektiv måte ved å kombinere additiv tilvirkning og konsvensjonell metallforming, for å produsere deler med høy kvalitet som kan utføre sin tilegnede jobb på en tilfredsstillende måte.

Søkeord: rørbøying, fleksibel dor, additiv tilvirkning, produktfleksibilitet, PLA.

Preface

This thesis was written at the Norwegian University of Science and Technology, at the department of mechanical and industrial engineering. It is submitted as a final paper for the master's degree in Mechanical engineering.

This thesis is a continuation of the specialization project in TMM4540 that was submitted autumn 2022. The workload has been distributed with 15 ECTS points for the pre-thesis work, and 30 ECTS points for this master's thesis. The work was conducted in a period from January till June 2023.

I declare that the work has been carried out independently and according to all examination regulations at the Norwegian University of Science and Technology.

Trondheim, 20^{th} of June 2023

Helena Treffen

Helena Treffen

Acknowledgment

First, I'd like to thank my main supervisor Jun Ma and co-supervisor Sigmund A. Tronvoll for very valuable input and guidance throughout this project work.

I'd also like to thank Xu He for being a valuable support for troubles in the lab and for using his valuable time to help me and my project.

I'd also like to thank my classmates for making it easier to come to school every day and for being friends to whom I can vent and pour any good and bad ideas, and for putting a smile on my face and laughter in my heart.

Lastly, I'd like to thank my mom and dad for always having my back and being a shoulder to cry on when times have been tough.

Abbreviations

RDB	Rotary draw bending
AM	Additive manufacturing
PLA	Polylactic acid
PETG	Polyethylene terephthalate glycol
FFF	Fused filament fabrication
FDM	Fused deposition modeling
CAD	Computer aided design
CNC	Computer numerical control
DOF	Degrees of freedom
NTNU	Norwegian University of Science and Technology
VEM	Value engineering method
NAPIC	NTNU Aluminium Production Innovation Center
DED	Directed Energy Deposition
SLM	Selective Laser Melting

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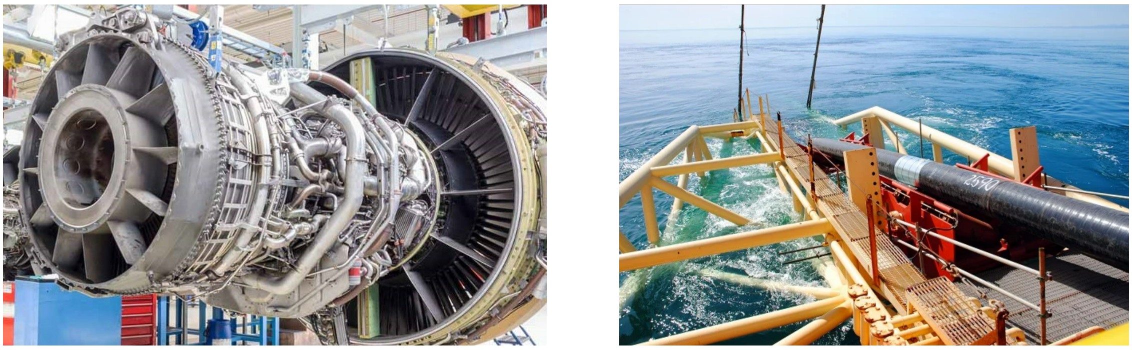
1 Introduction

1.1 Background and motivation

Bent tubes and tubular profiles are commonly used in a variety of fields to create lightweight, durable, and highly customized parts. Depending on the field of deployment, there are different requirements for the shapes and sizes, however, one thing that is always the case, is that they must all conform to certain standards and demands regarding quality, characteristics, and performance. Some fields with particular demand for lightweight tubular profiles are the automotive industry and the aerospace industry. While fields like oil, offshore platforms, and underwater sea systems are in need of massive, durable, and larger-scale tubes.



(a) Aircraft engine

(b) Offshore pipes

(c) Car chassis

Figure 1: Tubes in different environments (Shutterbox 2021).

In the current metal forming process, the design, development, and fabrication of machines, components, and tooling is normally expensive, requires high dimensional accuracy, and is relatively time-consuming. This makes for a process that ultimately is limiting to the transformation from the conventional machining, to more flexible customized metal forming.

The exact metal-forming process that will be discussed in the thesis is the process of rotary draw bending (RDB). This is a procedure that takes in a stiff tube and forms it into the requested shape and size. With a clamping mechanism, the tube is bent around a bend die that forms it into shape. The matrix of dimensions and parameters is large, and if wanting to have the possibility to produce a large quantum of different compositions, one would need a large inventory of tooling dimensions.

This is where additive manufacturing (AM) can come in as a novel and innovative solution to the problem. With the AM process, in this research constricted to fused filament fabrication (FFF) or fused deposition modeling (FDM), the whole metal forming process can possibly be optimized. Introducing a production process that is normally used for rapid prototyping and using material at a much lower cost, can offer a procedure that can produce low-volume components at a fraction of the price of a conventional manufacturing method. As the produced part is a part that can be used for rapid prototyping and use material of a much lower cost, it can offer an efficient procedure for making low-volume products that need customization for the RDB procedure. The outcome of the AM process can offer a part of plastic material with relatively comparable mechanical properties as a part that was made through conventional manufacturing, however with a much lower cost, and a more time-effective process.

1.2 Problem description

As mentioned in the introduction, customized tubing is needed throughout a variety of fields. And when the demand for more customized production processes grows bigger, there need to be presented new novel solutions to cater to the request. The change is when we go from mass production where tools and molds are rather rigid, into a production process that should be able to be changed depending on the level and ways you want the customized parts. The products from the manufacturing processes need to be of high quality and a level of precision that meets the requirements, as well as be able to mitigate the common defect factors such as wrinkling and cross-sectional flattening.

The problem is that making these types of customized tooling and components is a highly costly process, in the material choice, the manufacturing process, and the consumption and production time. The solution to the said problem would therefore be to develop a prototype for an additively manufactured mandrel die concept that can deliver a product with the same quality and performance as a conventionally manufactured mandrel, only reducing the cost, resources, and time spent in the production process.

1.3 Project scope

Overall, in the pre-thesis work, the focus has been on the bending of an Al-alloy tube with a wall thickness between 2- and 3mm. The work has focused mainly on forming a rigid tool that can act as a support in the bending process while providing a result that is satisfactory for development and future implementation in this tooling field. The tool kept a fixed location in the tube while bending and has only supported the tube at the exact tangent point of the bend, or at a positive extension into the tube.

The scope of this research in this master thesis is limited to the development and testing of a flexible AM mandrel in a tubular profile, that can be a further replacement of the already tested rigid AM mandrel from last semester. The aim is to see if the flexible mandrel can produce a more optimal tube bend, and if it is possible to decide the future implementation of the product into the RDB process. The materials and tubes used for bending have been limited to a 2mm wall thickness tube, as this is a wall thickness that is more prone to wrinkling and flattening of the cross-section. This results in an evaluation process that offers quantitative data, as well as clearer qualitative data that is easy to analyze.

1.3.1 Objectives

The aim of this study is to identify, prove or dismiss, whether AM tooling used in an RDB process can replace a conventionally manufactured tool. Through design, development, and testing of the products, it will be shown if they can perform to a level that is satisfactory. The tests that will be performed on the AM tooling should be compared to tooling of metal material, to have a basis for where optimal dimensions are located. Lastly, the results will be analyzed and evaluated to try to answer the research questions presented in the next sub-chapter. Later on, if the results are sufficient, this study can be used as a basis and starting point for future work and research regarding and in the field of AM replacement for conventionally manufactured metal tooling in different metal forming processes.

1.3.2 Research questions

1. How can one design cost-effective tools for more customized tube bending processes?
2. Can results from the test be used as a justification that other tools in the RDB process can be replaced?
3. Are the methods used now applicable to processes when bending with higher-strength tubular materials such as titanium and steel?

1.4 Thesis structure

The thesis is structured in a way that first presents the main problem description of the research, and the core as to why this research is important. Then a thorough literature review presents the current status in the field of AM in conventional machining, as well as theory on the basic procedures that are used in the project. Then the methodology used to achieve the results, including the development and improvements done to each iteration in the design process. Lastly, an overview of the testing and analysis results, what they mean, and how they influence further research and work.

2 Theory

2.1 Purpose and prerequisites

In order to be able to identify, analyze and evaluate the requirements, performance, and possible gaps, we need to have a total overview of the open source information. This is because the research done prior could be of benefit to the process, and give valuable information. To reduce the amount of work needed to be done prior to the project, a thorough literature review is therefore needed. The following chapter will present the available literature in the area of interest, as well as surrounding fields that can be of guidance and assistance. Many of the sections are borrowed from the pre-thesis as there was conducted a comprehensive literature review within the same field of interest, which is of high significance for this master.

2.2 Additive manufacturing

Additive manufacturing is the manufacturing technique that uses a material build-up to create three-dimensional objects. Specifically FDM or FFF printing within the realm of material jetting, which is the AM technique used in this thesis, layer by layer of thinly extruded material is deposited onto the next one. The layers are fused together, creating a three-dimensional model. Prior to printing, a model is created using CAD software. The 3D model is then sliced in a slicing software and converted into layers made with printer-readable code. The print is dependent on the process parameters, meaning thickness, infill, and orientation, as well as the specific AM technology. The different technologies can be identified in figure 2.

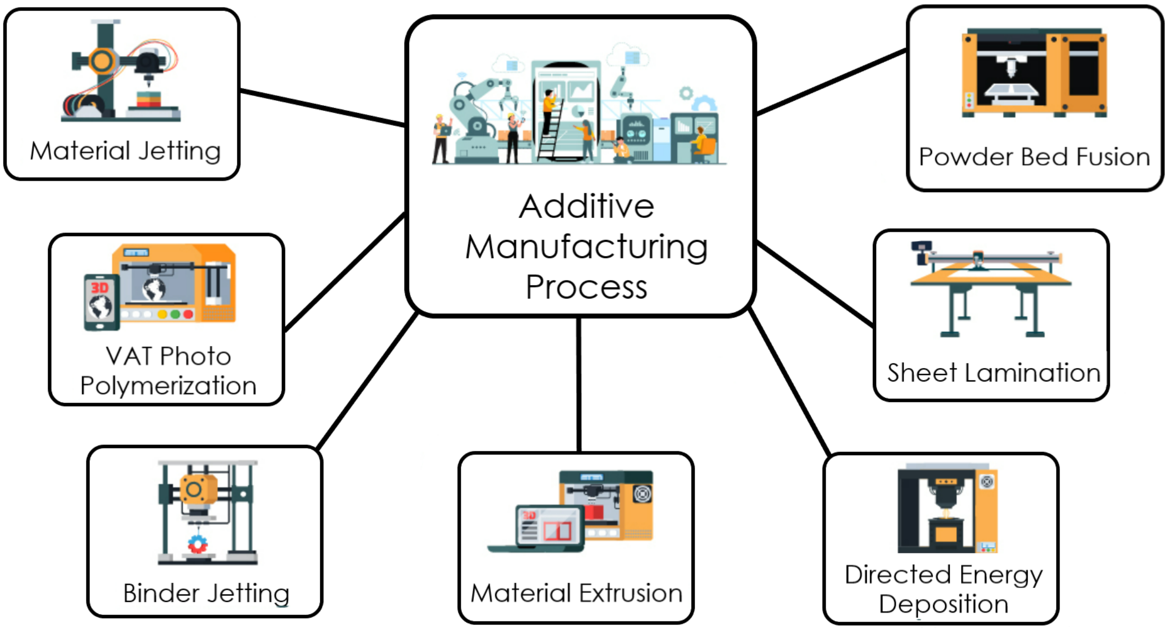


Figure 2: AM technologies (Kambale 2021).

With these methods of manufacturing, intricate parts can be made in a simpler manner than previously, with conventional manufacturing processes that could result in assembly processes that require multiple steps to achieve the desired result (Gao et al. 2021).

AM is generally not as fast as traditional conventional manufacturing techniques such as e.g., injection molding, and the cost per part may be higher for high-volume production. Additionally, some materials may not be as suitable for additive manufacturing, and the mechanical properties of AM produced parts are not as high as those of parts produced using other conventional methods. However, the main convincing advantage of using additive manufacturing for mass production is that it allows for the production of highly customized parts with minimal setup costs and a short lead time. Going from an idea to a model in physical form in a short time frame is largely beneficial to visualize concepts and rapidly prototype.

For customized parts, instead of having to create separate tools or molds for each part variation, the same machine can be used to produce multiple variations by simply changing the CAD file, and printing in a short time frame with effectiveness not seen before. For specific interest fields such as the aerospace industry, where demands and requirements for strength and weight are strict, parts can be manufactured with extremely strong material, and topology optimized to only have material where it is needed. This results in parts that are highly customized and optimal for the function and purpose, while significantly reducing the lead time and cost, compared to traditional conventional manufacturing methods.

2.3 Rotary draw bending

Rotary draw bending is a mechanical bending process that is used to form metal tubes and profiles into curved shapes with a specific dimension. In this process, a tube or profile is inserted into a clamp in the machine. Pressure and force are then exerted to clamp the profile down, as well as applied on the outside to force a bend around the bend die. The exact position of the bending happens at the line of tangency that goes through the center of the bending die, as observed in figure 3. After this point, the bending has stopped and the tube is curved around the bending die as a supportive measure. This type of bending allows for the creation of consistent and precise curves that are subject to minimal distortion of the metal.

When looking at the tube being bent, the inside of the tube is the side in contact with the bending die, intrados, while the outside of the tube is the side on the opposite side, extrados. During the bending process, two separate disfiguring instances occur at the same time. The first one is the strain on the extrados of the tube, resulting in a decrease of thickness in the wall as the material needs to distribute over a large surface area. The second instance is the intrados of the tube compressing and causing a material build-up, normally causing a wrinkling effect on the tube (Tronvoll et al. 2023).

Although a satisfactory bend can be achieved without supportive tooling as a mandrel, meaning supportive tooling inside the profile during bending, it becomes rather necessary when the wall thickness reaches a certain lower limit threshold, as it becomes significantly more prone to collapse, rupture, wrinkling and material thinning during bending.

This RDB process is commonly used in the construction of tubes and profiles of both steel and aluminum, for structures such as bridges, buildings, and parts for the automotive or aerospace field. There are therefore high demands for the product, and the process should produce high-quality products. However, as there is a vast majority of sizes and dimensions to the tubes and pipes that need bending, the process requires a high number of customized parts for each operation. Depending on the outside and inside diameter of the tube or dimensions of the pipe, parts such as the wiper die, bend die, clamp, and mandrel all need to be changed and made custom for the correct dimensions. If a bending company was to have the inventory for tubes in all shapes and dimensions, it would result in a very resource-heavy and time-consuming production process of parts, which becomes a costly interest when a multiple of profiles is to be processed in a customized tube bending process. Figure 3 shows an explanation of the components in an RDB process.

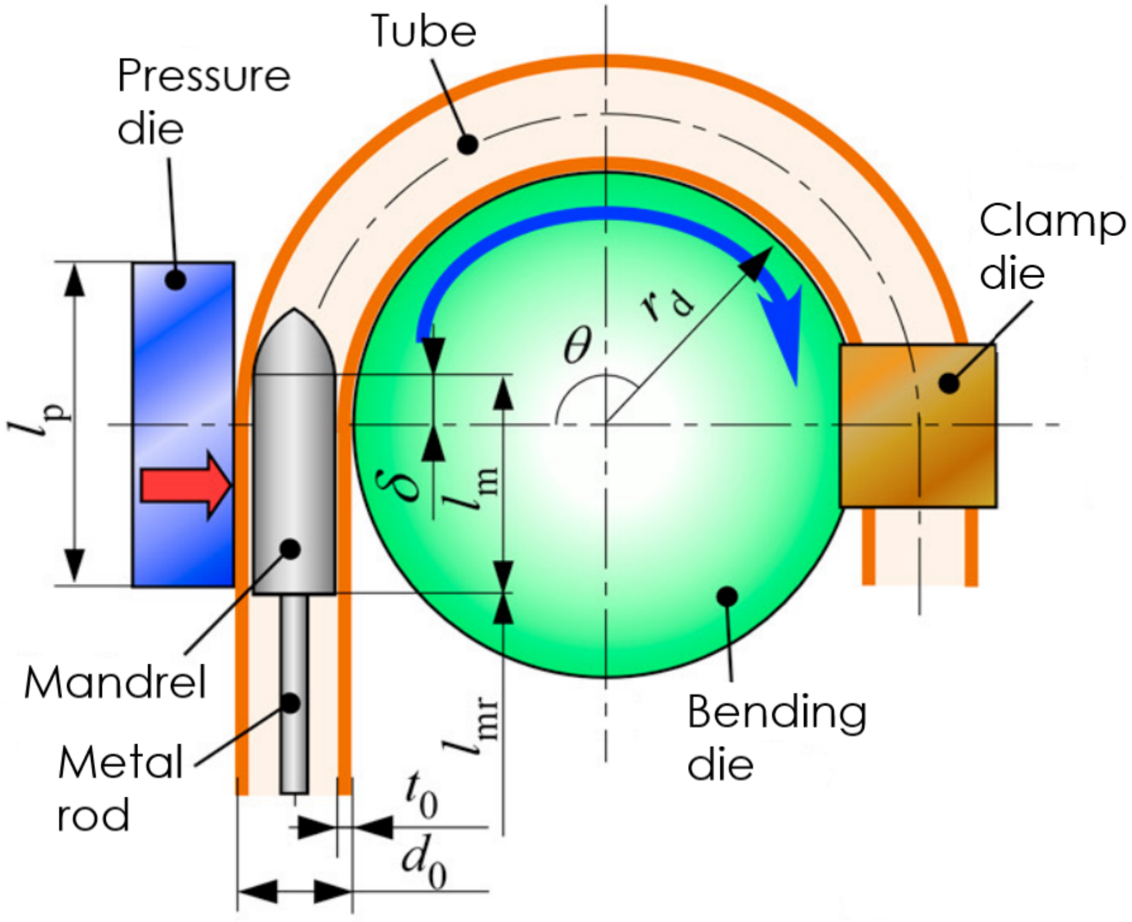


Figure 3: RDB process cross-section (Kajikawa et al. 2018).

2.4 Mandrel state-of-the-art

For both product development and production purposes, for a metal forming process such as RDB, it is crucial to have tooling that ensures that the respective tube has the ideal support, as well as the ability to mitigate the possible defects and weaknesses that occur in a bending process. This mitigation can be achieved by installing a mandrel onto the metal pole, specifically installed for the mandrel.

In an RDB machine, we can categorize the different mandrel selections into three main groups; a rigid mandrel with a spherical tip, a bend radius mandrel, and lastly a flexible mandrel. All the categories serve the main purpose of providing instantaneous support, with mitigating wrinkling and collapse during bending, although they differ in overall performance. A rigid mandrel would naturally only provide support in the exact position it is placed, while a flexible mandrel will have a larger area of contact, resulting in more coverage and support after the bending point.

Generally, the need for a mandrel is dependent on and determined by the tube geometry and bend radius, and is not always a necessity. The general guideline is that whenever the center line radius to the outer diameter of the tube ratio is smaller than 1.7, then a collapse will inevitably occur, with the ability to mitigate this with the use of a mandrel (ASM 1969).

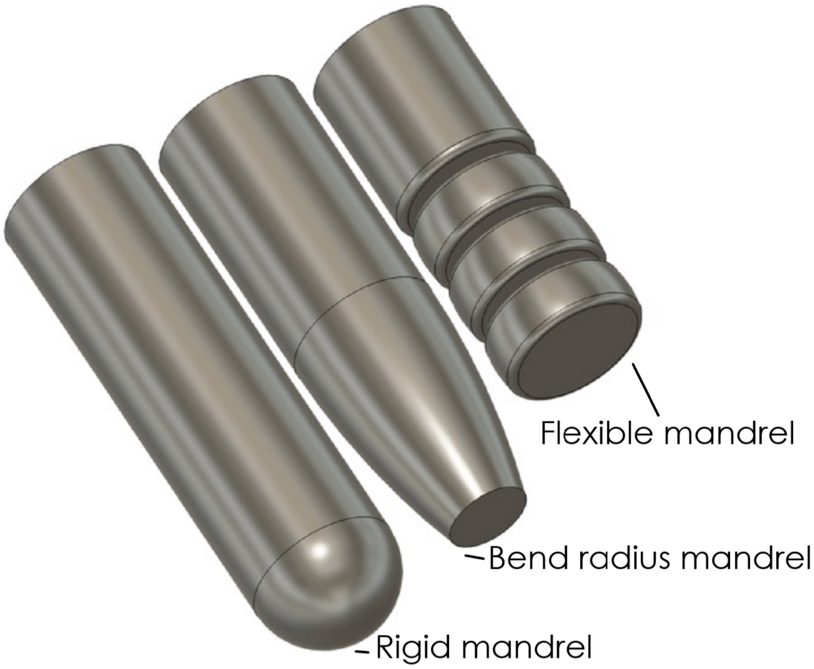


Figure 4: Mandrel categories (Ma 2022).

Making a conventional metal mandrel usually acquires high-precision manufacturing, with a CNC-machine or other precise clear-cut machines. This makes for a process that requires many resources, and time and is of high cost for each iteration of the mandrel that is needed. Considering the number of tubes with diverse wall thicknesses and dimensions widely vary, a disadvantage is the large inventory of mandrel sizes a workshop has to hold, to be fully functional and able to deliver a product to the customer.

Further analysis of mandrel performance and optimization can be seen from a study performed in the field where mandrel position was the main theme (Kajikawa et al. 2018). The study shows and concludes that the tube end quality after bending is largely dependent on the mandrel positioning in relation to the tangential bending point. The position in question is the measured distance from the tangential point, meaning the exact position the bending occurs at, and to the displaced distance either forwards or backward from the point. The axis and direction of positioning are determined to be forwards when the mandrel moves into the already bent tube, while backward implies towards the unbent tube. The study has shown that with a positive displacement distance, meaning a displacement forward, the mandrel was able to mitigate more wrinkling and improve the overall defect reading. Moving the mandrel backward, however, increased the wrinkling and irregularities in the finished bent tube.

Another study performed by Li Heng et al. addresses a flexible mandrels impact in a precision bending process of a thin-walled tube. Factors such as mandrel diameter, extension, chain link number, chain thickness, and nose radius are discussed, as to what values and angles are optimal. And also this study confirms the data from previous studies mentioned. With an increase in extension length and mandrel diameter, the overall anti-wrinkling ability is increased, however, not to overcompensate over a certain threshold, as this results in over-thinning of the extrados. In regards to chain link amount, the study shows that up to a certain amount, found by a purposed formula in the study, an increase in chain links is positively helping the cross-sectional distortion(Heng et al. 2007).However, the conventional production of these mandrels demands a high precision CNC-machine, as well as some post-processing (Salem et al. 2015).

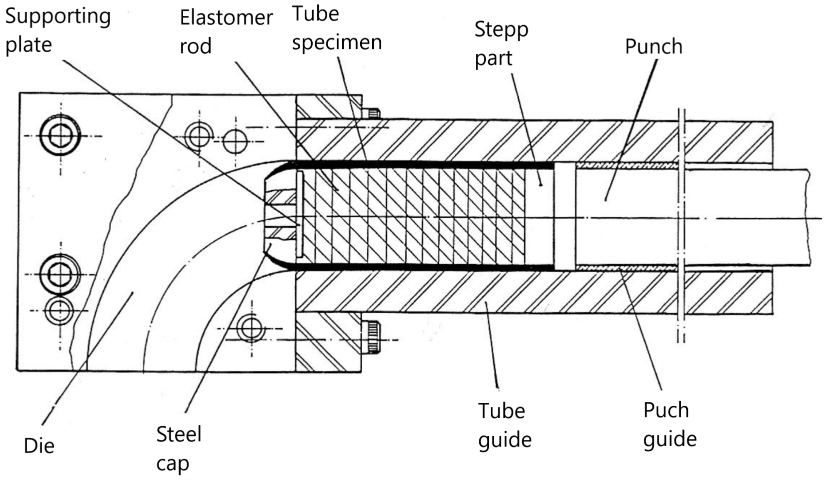
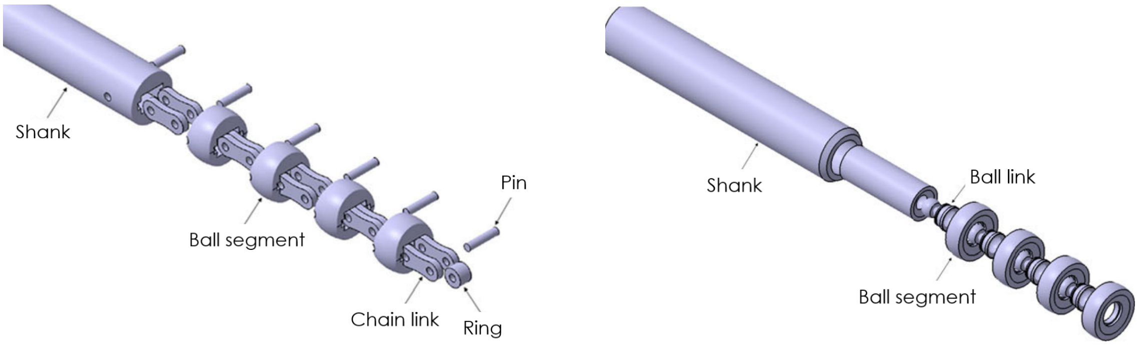


Figure 5: Bending tool cross-section with elastomer (Al-Qureshi 1999).

H.A. Al-Qureshi et al., although an old study, exploited the use of elastomer material, as seen in the cross-section on figure 5, as a metal replacement for a flexible mandrel, and concluded that with the right tools, the bending can be carried out with success, as a simpler and cheaper alternative to conventional bending tooling (Al-Qureshi 1999).

Lastly, in close relation to the mandrel this master aims to develop, is the study of M.Salem et.al, where an experimental and finite element analysis of a metal chain link mandrel is conducted. The mandrel from the study, figure 6 (a), is designed to have the possibility of change in orientation through rotation over only the transverse axis, meaning pitch, in comparison to the ball link mandrel, figure 6 (b), that can orient over pitch, yaw, and roll. When this type of chain link mandrel is installed in an RDB machine it must be ensured that the mandrel rotational axis is in line with the neutral axis and plane of the bending, as the mandrel will not perform optimally if not, and can displace during bending.

Compared to a ball link mandrel, the chain link mandrel is of lower cost during production, as well as it has a greater mechanical strength during bending. When comparing the two mandrels through both simulation and experiments, it can be seen and concluded that the chain link mandrel can provide good performance and a significant reduction in ovality, or flattening, of the tube (Salem et al. 2015).



(a) Chain link mandrel

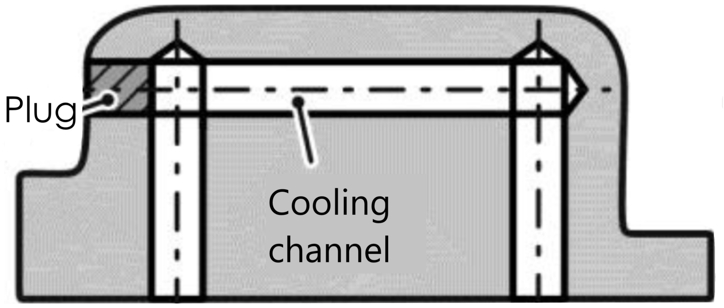
(b) Ball link mandrel

Figure 6: Flexible metal mandrels from M.Salem study (Salem et al. 2015).

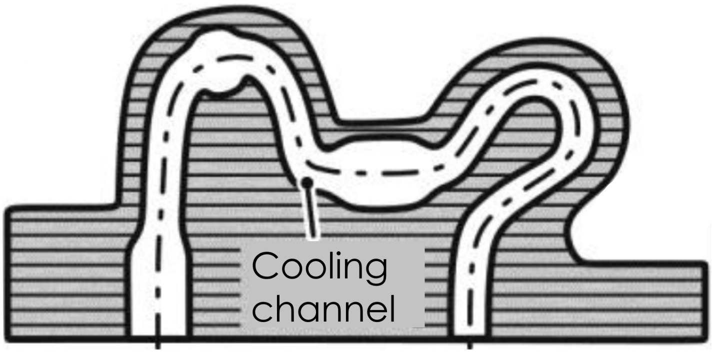
2.5 AM tooling for metal forming

Although the production of tooling specifically for RDB has not been attempted before, the production of these types of AM tooling has been introduced in other fields. A research program by D. Chantzis et al. was conducted, where the aim is to evaluate and optimize the process of hot stamping. This is a leading process for forming high-strength materials, such as steel and aluminum, and is a process that requires large magnitudes of both heat and force. The tooling needed in the process must therefore be able to withstand harsh conditions to ensure an optimal result for the produced components. This is where the AM presents itself, making it possible to produce tooling with specific cooling ducts and passages, to neutralize the heating problem present. The study shows great promise, and results that support the implementation of AM in tooling making, but there are however still problems and gaps that need to be filled before a solution can be set fully to life successfully. Factors such as material selection, where they need to find a suitable material that can withstand the environment it will be operating in. Other factors such as defining a rule set for the design, to be able to create and develop components that are feasible to produce despite the complex structures needed in the process (Chantzis et al. 2021).

Another study was conducted in a similar field, where AM has been used as a main manufacturing method, in the making of cooling equipment for for the enabling of increased production speed. The study showed an increase of almost 300% and consequently proved that introducing AM in tooling production can not only reduce the costs and resources used but also significantly reduce the lead and production time. This is because of the ability to produce complex geometry parts with canals and ducts in a way that conventional machining isn't able to manufacture (Holker et al. 2015).



(a) Conventional subtractive machining



(b) Additive manufacturing

Figure 7: Cooling ducts from study (Holker et al. 2015).

In a study from the University of Seigen in Germany, they tried to optimize the production of car components with AM technology, where a die for production was the main issue. Despite the large heat and operational forces the die is subject to during production, it was able to provide data proving that an AM die was performing at a satisfactory level during the process and was producing quality parts without major defects (Frohn-Sörensen et al. 2021).

When using additive manufacturing for producing metallic and polymeric rapid tools for sheet bending, as they have done in a study conducted by M. Strano. The paper shows that the technique of AM proves as a viable option for producing different tooling. However, there are some limitations when it comes to fatigue life due to the porosity of the printed parts, as they can not withstand the forces a conventionally machined tooling could. The cost of manufacturing metal tooling with conventional metal forming processes is high and demands a significant amount of resources to be produced (Strano et al. 2021). AM-produced tooling, however, is cheaper, faster to produce, and requires fewer resources.

Another form of research where AM was used is for example in the study from A. Komodromos where they printed integrated cooling channels by directed energy deposition, DED which was used in a hot stamping process. DED is a form of AM and makes it possible to manufacture cooling channels that can reduce the heating of the tools and the surface, which again plays a part in the final material properties of the stamping process (Komodromos et al. 2022) Although the AM process did not use plastic material, it can still conceptually show how AM can be beneficial for multiple production processes although the material fields are different.

2.5.1 Cost aspect of AM vs. conventional machining

There has been done an extensive study on the comparison of AM to conventional machining at the Politecnico di Milano, where the case study focused specifically on the production process of dies for tube bending. The AM technology was SLM, which is selective laser melting, using metal additives and material that is melted layer by layer. To conclude the study, when observing an SLM part without having done any alteration to the part, it is not yet viable compared to the conventional process. However, the factor that is more difficult to evaluate, such as the ability to significantly reduce the weight of the part, which again reduces the production time and increases the overall part performance, can be of high value and weight for the SLM-process but needs more analysis of the production life to be assessed (Previtali et al. 2020). This study is however not completely comparable or compatible with this thesis, as the study researched the AM technology that is SLM. This is an AM process that uses different metals, which are neither cheap to buy to form. The AM technology used in this thesis is FDM, which used plastic polymers that are significantly cheaper to buy, as well as the machines needed to print the wanted parts.

2.6 Project specialization

The specialization project was a pre-thesis study to find literature and develop and test a novel product that could solve the main issue. The main objective was to design and develop a rigid AM mandrel to replace the conventional metal mandrel that is present in an RDB process. A prototype was made, and after a few iterations and testing, the final evaluation and analysis of the product could conclude with a successful result. Although it wasn't completely possible to put a qualitative value to the actual comparability of the metal and AM mandrel, the mandrel was able to prove that it can provide the structural integrity and supplementary support needed during bending. This was proven by measuring the flattened cross-section before and after bending, as well as comparing the result to the metal mandrel results. At the maximum extension of the AM mandrel, 10mm from the origin, the performance was more or less equal for both mandrels. Although there are many positives, it has not yet been possible to provide data on how durable and resistant the AM mandrel can be, as this demands cyclic testing over a longer period of time.

2.7 Literature gap

The literature found during research has been of high importance to the thesis. The different studies where AM has been introduced into other metal-forming processes can be beneficial to use, as the tests completed in the different studies can be a potential foreshadowing of the results we can collect in the study. However, the has not been a comprehensive study done on mandrels in RDB, and there is a definite literature gap that needs to be filled with new research.

3 Methodology

3.1 Process explanation

This chapter will present the approach and implementation of the design and development, the conduction of tests, and finally the data acquisition of data. A short introduction of the pre-study design will be presented to highlight what has been done and how the groundwork and results of these have been exploited to make a new novel design. Each design will be presented shortly with the most important iterations.

3.2 Value engineering method (VEM)

During the conduction of this thesis, it has been important to approach the work with a plan and a well-set method. The method that has been followed is the conventional value engineering method which goes through a multi-stage plan. It has a large focus on continuously identifying possible improvements to the value of the product and process, hence increasing the functionality while simultaneously reducing the cost and resources required in the process. This results in an optimized method that labors on efficiency in the process while developing a top-notch product (International 2007).

The steps of the conventional value engineering process include the following steps and will be explained in the following chapters:

1. Preparation
2. Information
3. Function analysis
4. Creativity
5. Evaluation
6. Development
7. Presentation
8. Implementation

Using this approach gives the final product an optimal balance between form, function, performance, and resources and cost put into the project. The chapters will chronologically go through the steps while introducing what has been focused on in each chapter. This approach is the same one used in the pre-thesis work, and there are already points that have been covered, as well as points that need more work. This overview can be summarized in the course-of-action matrix in table 1, presenting what is done and what needs to be completed.

	Explanation	**Project thesis**	**Master thesis**
Preparation	Learning RDB machine and basic workshop standards.	Yes	No
Information	Literature review of the available theory surrounding the subject. Identifying the literature gap.	Yes	No
Function analysis	Identifying all requirements for the part to optimally co-exist with the surrounding area.	Yes	No
Creativity	Exploring and deciding on the possibilities of different mandrel designs. Development and production of mandrel solution.	Yes	Yes
Evaluation	Testing, evaluating and modifying mandrel solution based on testing in the lab.	Yes	Yes
Development	Final development and production of the product.	No	Yes
Presentation	Collection of the results from testing, and compilation of the results into the document.	Yes	Yes
Implementation	If the product is valuable and performs up to standard, a real implementation into the working RDB system is possible.	No	No

Table 1: Course-of-action table based on the VEM.

The course-of-action matrix shows that a majority of the process has been conducted in the pre-thesis work, together with some work to be done in this master thesis. However, a lot of the process, from the points of creativity to presentation, is to be repeated. This is because of the further development of the product goes in a different direction and therefore has needed new brainstorming and evaluation. Implementation of the parts as a standard in the RDB process is not yet completed, as the metal mandrel is present and shows the best performance. However, with more testing and analysis it could be concluded in the future that the AM mandrel could hopefully perform at the same level.

3.3 Preparation and information

The previous chapter concerning the literature review has presented a significant gap in the field of mandrel bending and AM-production of tooling. It has therefore been important to use the available information effectively but with a critical mindset, as it can not fully provide the information needed to draw all conclusions.

3.3.1 Information

All information gathered in the pre-thesis work can be used directly and without any major intermediary. The results from the pre-thesis are also the prerequisite to be able to continue the work and challenge the design further on, as the design in this thesis is the basis of the initial design from the pre-thesis.

It was stated in the pre-thesis conclusion that the rigid mandrel as seen in figure 8 did in fact provide the structural support needed to significantly reduce the flattening of the tube. The mandrel did also provide data showing that, at maximum extension, it had a sufficient enough performance level compared to a conventional metal mandrel. The pre-thesis has therefore given a green light to further development of the mandrel, where the specific focus is on the continued development of the flexible additively manufactured mandrel.

This mandrel will be a tooling component that can better support a tube while being bent and should have links and parts that can move freely with the tube it is entering, while still being strong enough to withstand design and preparations have taken the basis from this rigid mandrel that has already been developed.

Figure 8: Mandrel prototype from pre-thesis work.

3.4 Functionality analysis and requirements

3.4.1 Requirements

It is important to identify the function that a produced tooling support should have to be able to determine what areas should be of focus in the product design and development process. Points such as the product's longevity and durability, as well as any compatibility and compliance with other components in its surrounding environment are of high importance. The following requirements are of the highest necessity for the product to be made:

- Product is compatible with the original metal rod that is a semi-stationary part of the RDB machine.
- Product is compatible with the metal insert.
- Product has sufficient clearance for a smooth insertion into the tube, as well as onto the metal insert. Lubrication gives a smoother assembly, as well as a better result.
- The product must offer structural support both during and after bending.
- Product should offer comparable structural support as its equivalent brother in steel.
- Product must have the ability to be ejected smoothly out of the tube.
- Product must show durability and longevity from active repetitive insertion and dismantling of the tube.

With the requirements stated, it is possible to develop and identify the design space needed for the part, as well as understand how the part needs to be designed in order to conform to the requirements. In the next chapters, the possible solution to the problem will be presented.

3.4.2 Performance parameters

Furthermore, in order to be able to evaluate how the mandrels perform during testing, identifying and stating the performance parameter is a necessity. These are parameters that the mandrel can be checked with to see how well it performs in the given points. The identified parameters are:

- Wear and deflection in tangential point on the mandrel.
- Mitigation of aluminum tube wrinkling.
- Scraping and wear on the inner surface of the tube.
- Measured cross-sectional flattening.

3.5 Creativity and development

The mandrel development focuses on making a product that meets the requirements set for the system, and that can be a solution to the problems that have been stated in the introduction. During this thesis work, it is important to brainstorm and let creativity flow to find the best possible solutions for the problem. The solution has become a product that has taken two different turns while being developed in a parallel workflow. The first is a flexible mandrel fully made out of additively manufactured parts, while the other is a steel core with an AM-printed outer skin.

3.5.1 AM flexible mandrel

The AM flexible mandrel is a continuation of the static solid mandrel that was developed in the pre-thesis. The removable links are all made out of additively manufactured parts, and connected with a wire to keep the links together. The challenging part is to find a solution that ensures that the links are durable enough to connect to the stationary metal rod, as well as also connecting the links together. The most obvious solution has been to drive a wire through the center holes of the links while separated by nuts to get the right spacing for free flexible movement of the mandrel.

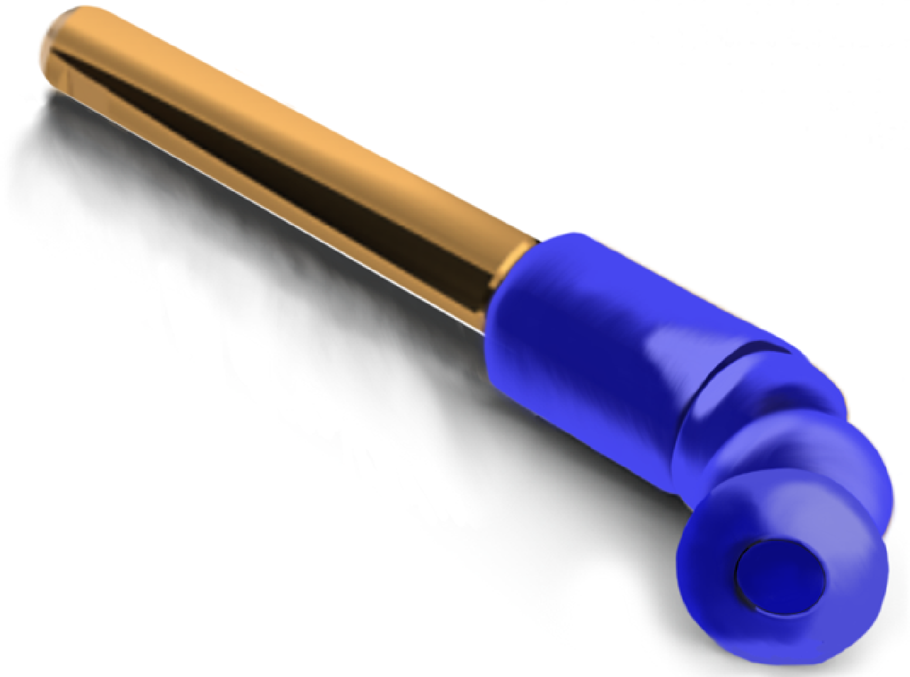


Figure 9: Early prototype of AM mandrel.

The complex part of the design process, however, is making the connections between the links seamless enough. The higher the friction between the connections, the higher the wear will be on the connection. This will in the long term lead to a looser fit of the connections, which again can lead to a decrease in dimensional accuracy.

3.5.2 Metal core mandrel with adaptable outer shell

This version of the mandrel is based on a conventional flexible metal mandrel. The metal mandrel is acquired from a supplier specializing in metal mandrels, both flexible and stiff. The solution has been to dismantle the part with direct contact with the inner surface of the tube and then replaced it with additively manufactured parts. The AMed parts are therefore referred to as the shell of the mandrel, as the core is the default inner chain.

The shell must be modified to handle the forces and stresses it is subject to, but would connect to the metal core in the same way as the original part. This provides a solution that is highly adaptable, as the shell can be disassembled and replaced with parts that can fit different diameter tubes. This makes this solution eminently more adaptable while mitigating the need for a removable inner core connection.

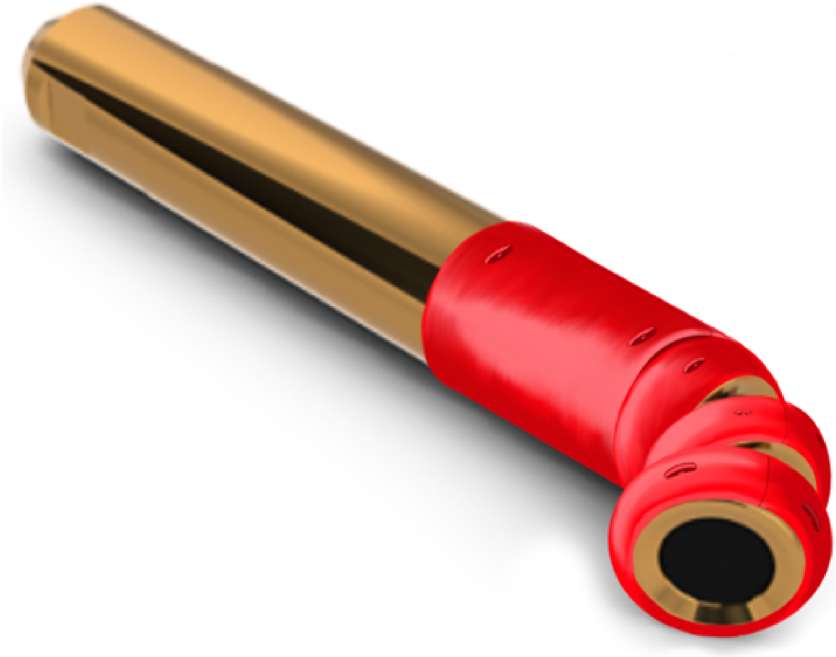


Figure 10: Early prototype of the steel core mandrel with AM shell.

3.5.3 Parallel workflow

As the two mandrel designs are fundamentally different, the workflow of the process has been to work in parallel on both designs. While waiting for the metal mandrel core to arrive from the supplier and other parts to be manufactured in-house at the NTNU metal lab, the development and testing of the AM flexible mandrel have been ongoing.

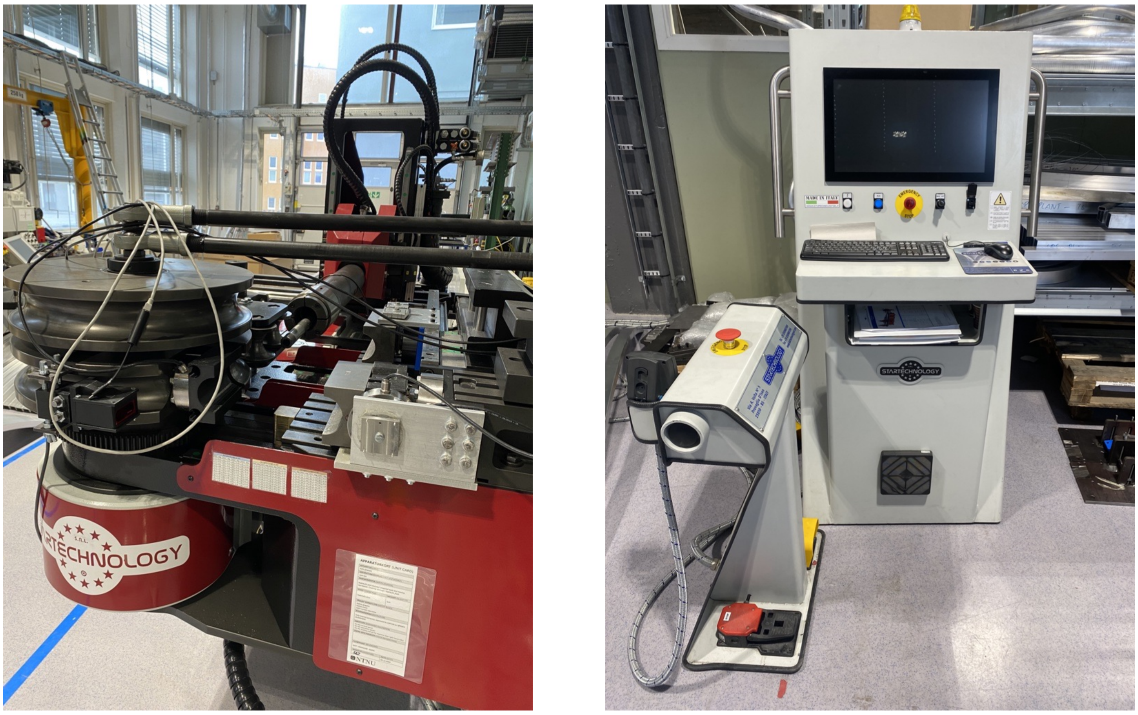
The testing of the AM Flexible mandrel has been done in multiple steps, as through testing and general discussion there have been found features and components to improve, add or remove. The focus has in the beginning therefore mostly been on the AM flexible mandrel, while waiting for the metal mandrel core to be manufactured.

3.6 Experimental set-up

The following chapter will present the setup of all things concerning experimental testing and lab work. From the set-up of the machine, what and how the different design iterations are tested, to last the collection of the data gathered.

3.6.1 RDB-machine setup with software

Conduction of the test for the two mandrel iterations has been conducted in the NAPIC lab at NTNU, in a Star Technology 800 EVOBEND rotary draw bending machine. The software setup is calibrated to the specific tooling that is installed at the time, and the default setup that is used for this project is a tooling design for Ø60mm profiles with a 222mm bend radius. The mandrel is screwed onto and connected to a metal rod specifically used when bending with mandrels, that goes along the axis of the RDB. Figure 11 shows the overview of the RDB system with a mandrel installed.



(a) RDB machine

(b) Computer to control RDB

Figure 11: RDB-system with computer and console.

The software setup of the machine is calibrated with the tooling that is installed in the machine, and it must be ensured that the tooling components are equivalent to the ones in the software. After starting and setting up the system, a final ”homing” of the components must be executed to ensure that all components are in the correct initial positions for bending. The machine is now ready to be used.

When installing the mandrel, it is important that the mandrel tangential point, as seen in figure 12, is calibrated to the correct point on the RDB. This is the point on the mandrel that will tangent the tube in the exact spot when the bend occurs and is crucial for an optimal bend. The manual control console, as shown in figure 11 (b) can be used to change the mandrel position displacement.

Lastly, the mandrel will benefit from being lubricated to smooth the two surfaces that will be in contact with each other and reduce the general wear that is present.

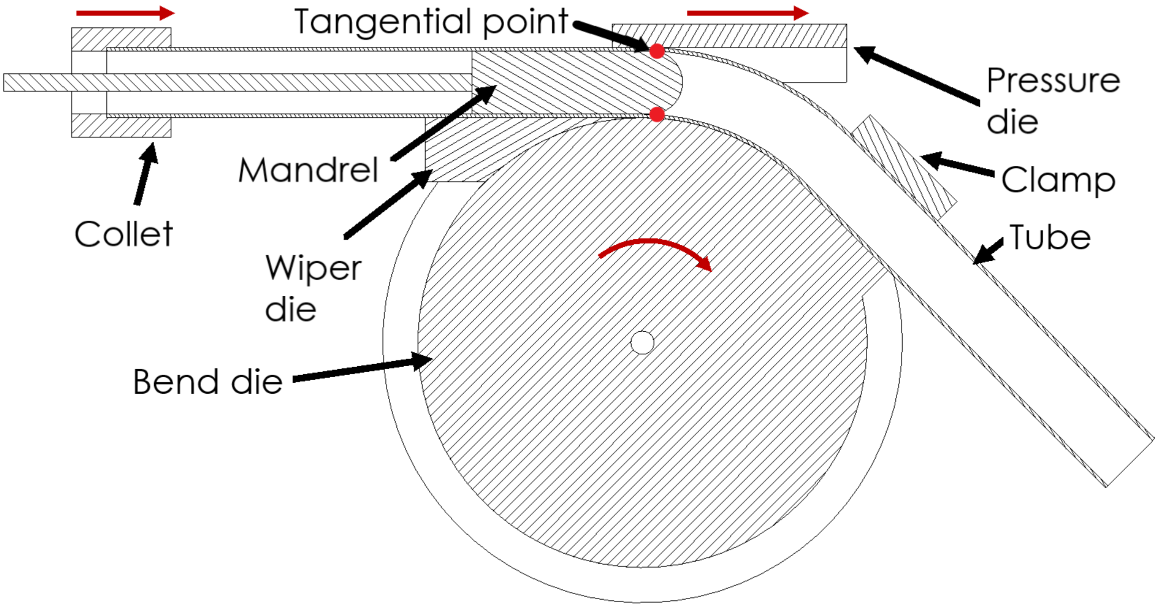


Figure 12: RDB-machine overview (Ma 2022).

The pre-thesis work presented a conclusion for the extension distance, which is the increase of distance between the tangential point and the displacement of the mandrel inwards into the tube bend. When testing at a displacement distance between 0-10mm of extension from the tangential point, it was concluded that the mandrel did perform its best at the maximum displacement extension of 10mm. Although a larger increase wasn't tested, it is expected that 10mm is nearing the maximum optimal displacement distance for the mandrel. This is however not crucial information for this thesis' experiments, as the main focus has been to test the general concept primarily, before trying to optimize the process. The optimization of the process is a concept for the future continuation of work.

3.6.2 Test specimens and matrix

The tubes tested for the project were aluminum tubes of the material Aluminium 6082 with the dimension of 60mm in diameter, Ø60, and 2mm thick walls. For testing, each mandrel should be tested on a minimum of two samples to ensure that the results of the test are unambiguous, of quality, and repeatable. The designed and developed components on the AM parts of the mandrel are of the material filament PLA, which is a low-cost, relatively durable fused filament material.

In table 2 we can see an overview of what mandrel types were tested, the tangential extension, and how many samples were tested.

Experiment no.	Mandrel type	Tube type	no. of samples
1	Flexible AM mandrel	2 mm	1
2	Metal core mandrel	2 mm	6

Table 2: Overview of experimental testing.

The specimens in figure 13 show the two different mandrels; the flexible AM mandrel and the metal core mandrel, and the different iterations of them. The multiple has been tested in the RDB, while some were iterations that were concluded to most likely not pass the test, and therefore scrapped from testing.

Figure 13: Mandrel overview.

3.7 Collection and presentation of data

The data gathering in the pre-thesis was focused on mostly the deformation and how much the cross-sectional deformation decreased. The points were measured at five different measuring points along the bend of the tube, and compared to the original cross-section of the tube. There were two variations of the tube, with a 2- and 3mm wall thickness. However, the 3mm tube was the test object for most of the tests, and the focus was therefore on how the cross-section changed, and not so much on the optical defects such as wrinkling and cracking. This is because a 3mm thick tube does not exhibit the degree of wrinkling defects without a mandrel as a 2mm tube does, because of its ability to withstand much of these defects.

On the testing for the flexible mandrels, however, the focus has been more targeted on the ability the mandrel has to mitigate optical, and qualitative defects, as the main testing specimen was a tube with 2mm wall thickness. Since this wall-thickness tube is more prone to wrinkling and cracks, the mandrels could more easily give an indication of whether or not it is working. As the wrinkling should be easier to mitigate if the support medium is good, the results are simpler to read.

The method used to gather the data from the test will be the same as for the pre-thesis. A quantitative evaluation with a caliper at five different measuring points in the bend, as well as a qualitative evaluation of the mitigation of the wrinkling defects. The data will be put into graphs and compared to bending without a mandrel and with a metal mandrel. This ensures results that can easier answer the research questions given.

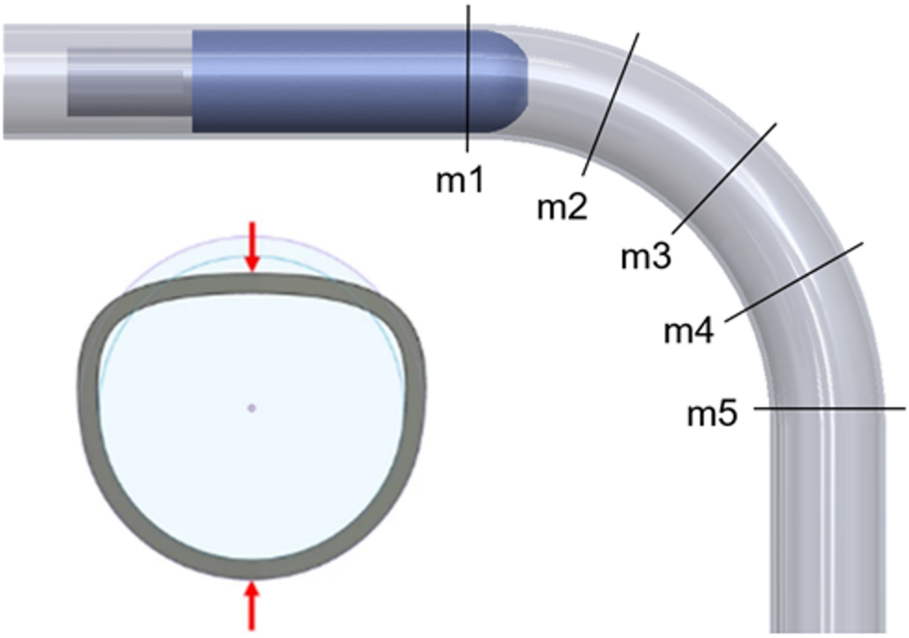


Figure 14: Measuring points for quantitative evaluation of result.

From previous experience and testing it can be concluded that a 3mm wall thickness tube can withstand significantly more wrinkling defects than a 2mm tube, if bent without a mandrel, as seen in figure 15 where the two tubes are compared. Again, it is therefore easier to qualitatively evaluate the flexible mandrels' ability to mitigate and reduce wrinkling, as well as verify if the general concept really works. The test will therefore first and foremost be tested on the 2mm tubes, as they can easier present qualitative improvements from the mandrel, and second in line, test on 3mm wall thickness tubes.

(a) 2mm wall thickness

(b) 3mm wall thickness

Figure 15: Wrinkling defects from RDB without mandrel.

4 Product development

The mandrel development focuses on making a product that meets the requirements set for the system, and that can be a solution to the problems that have been stated in the introduction. During this thesis work, it is important to brainstorm and let creativity flow to find the best possible solutions for the problem.

As stated in the previous chapter, the process has been divided into two possible solutions that have run in parallel. The first part is a fully AM mandrel with links only produced through FDM. While the second direction is using a metal mandrel core, and customizing the outer shell to fit the tubes. The following designs will be presented in this chapter, along with all the different iterations that were of importance to the development process. The rapid prototyping process is pictured in figure 16 below.

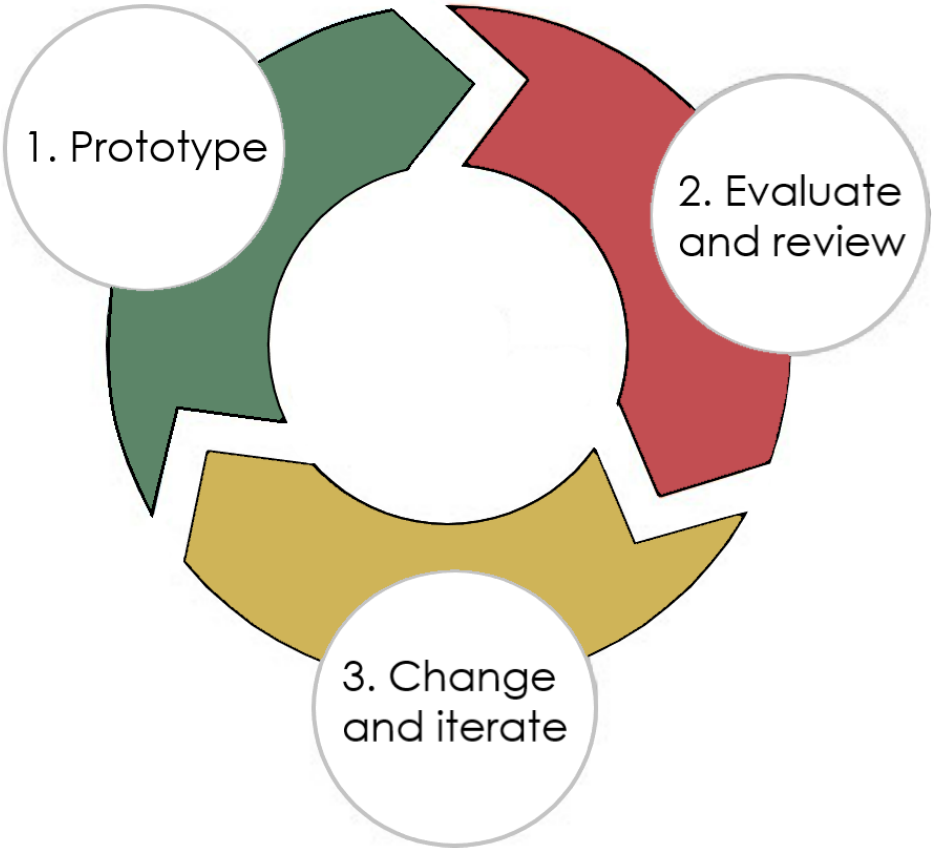


Figure 16: Process circle of rapid prototyping.

4.1 AM flexible mandrel: initial design

The initial AM flexible mandrel is the first prototype of the AM mandrel product. It has been inspired by different flexible gadgets and takes a lot of inspiration from bionics when it comes to the movement and flow of the flexible chain link chain. The design is a static pole with a flexible tip that can move together with the tube it is inserted into.

4.1.1 Dimensions and components

For a Ø60mm tube with a wall thickness of either 2mm or 3mm, the given clearance needed for smooth insertion and ejection between the tube and mandrel is 0.2mm. This makes for the tightest fit as well as ease of assembly.

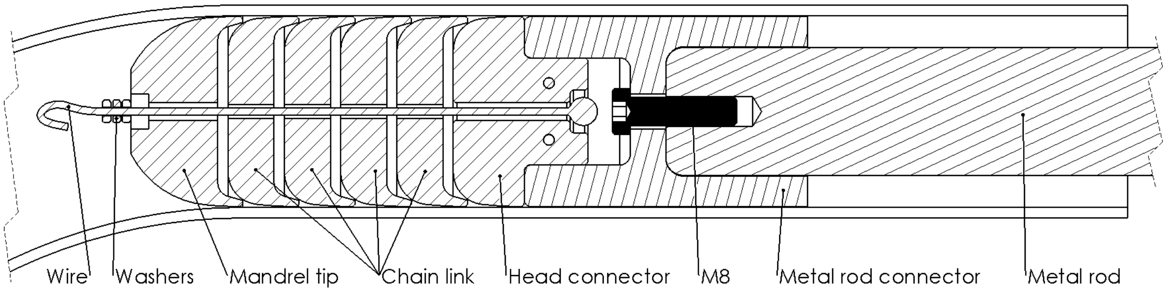


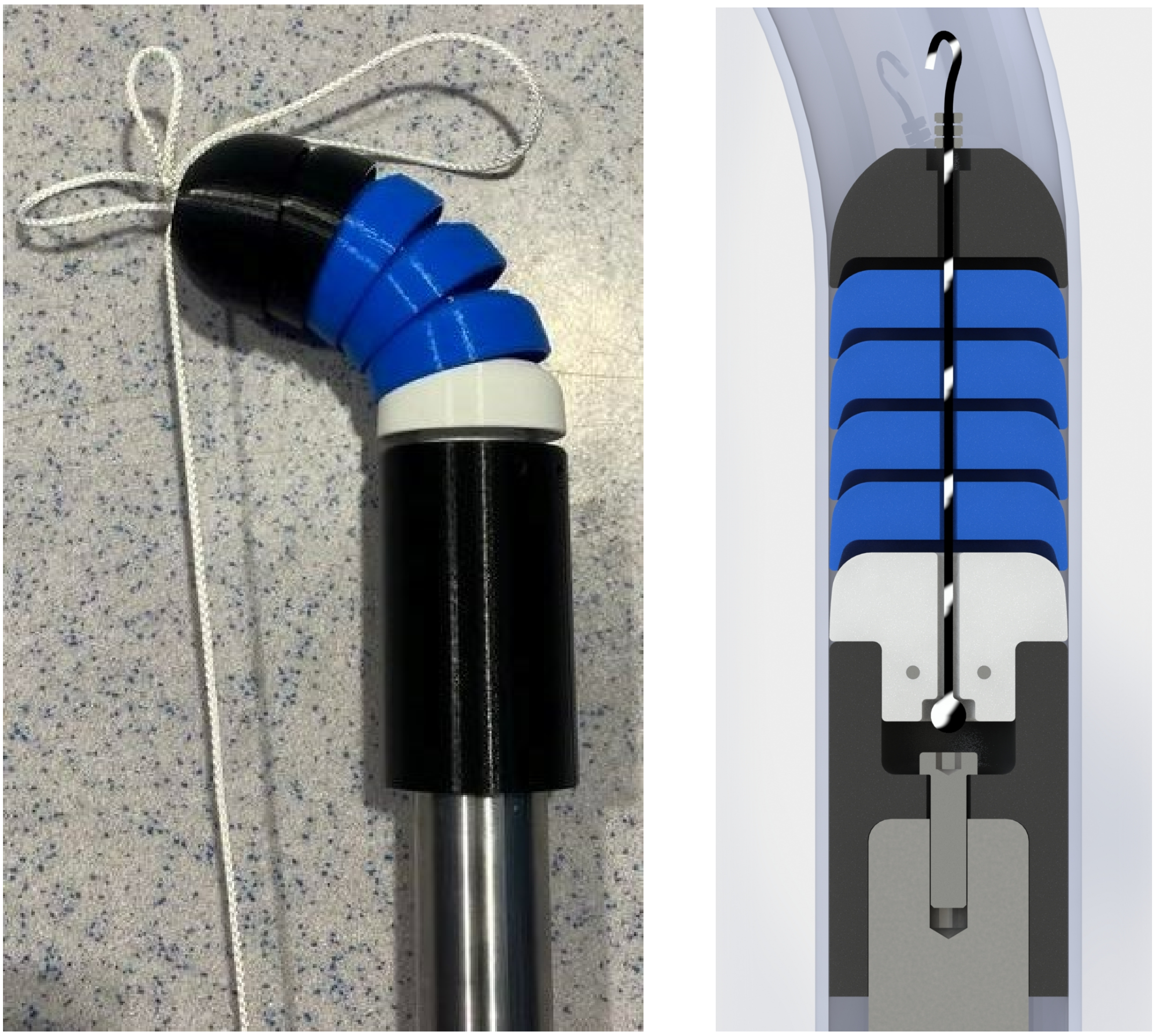
Figure 17: Cross-section of initial mandrel design.

This mandrel can be divided into two groups; the first group is the flexible part with the head connector, four chain links, and mandrel tip, while the second group is the metal rod connector. Figure 17 shows the cross-section with the respective component names. To connect the parts, a wire has been run through the center holes of the mandrel, with a stopper in one end, and fastened and tightened with removable self-made washers by the mandrel tip. During assembly, it was evaluated that the design could benefit from having washers or nuts in between the chain links in order to make the mandrel more flexible and movable.

4.1.2 Mandrel assembly

The metal rod is the rod that is screwed onto the original static 4m metal pole on the RDB machine. The metal rod is then inserted into the metal rod connector and fastened with an M8 hex socket cap screw. With the M8 screw fastened tightly, there is space for the wire stopper. The next step in the assembly is to thread the head connector, as well as the four chain links and mandrel tip onto the wire. The parts are stopped from falling off by tying the wire in the end and fastened with pre-made washers.

The two parts; the flexible chains and the metal rod connector are now ready to be connected. The flexible rod with the head connector on the bottom is placed into the metal rod connector, and to fix them together, two M3 hex socket cap screws are screwed into place, running through the whole diameter of the part. When the M8 screw is fastened tightly, the screw and wire stopper can coexist in the free space between the two connectors. In figure 18 the cross-section of the mandrel shows how the chain links are connected, as well as the connection to the metal rod. The string was a temporary solution to a more suitable metal wire. A Ø1mm metal wire should be fitting for the stresses and forces present during bending, but testing will give more information on the subject.



(a) Assembled mandrel (b) Cross-section of mandrel

Figure 18: Initial flexible mandrel design.

The wire stopper in the free space between the connectors is in this iteration not yet optimal. When assembling, the solution has been to twist the wire around the M8 screw, tighten it and form a seal around with the wire. This creates a fixation point for the wire but at a possible cost of damaging the wire, exposing it to fracture.

4.1.3 Advantages and disadvantages

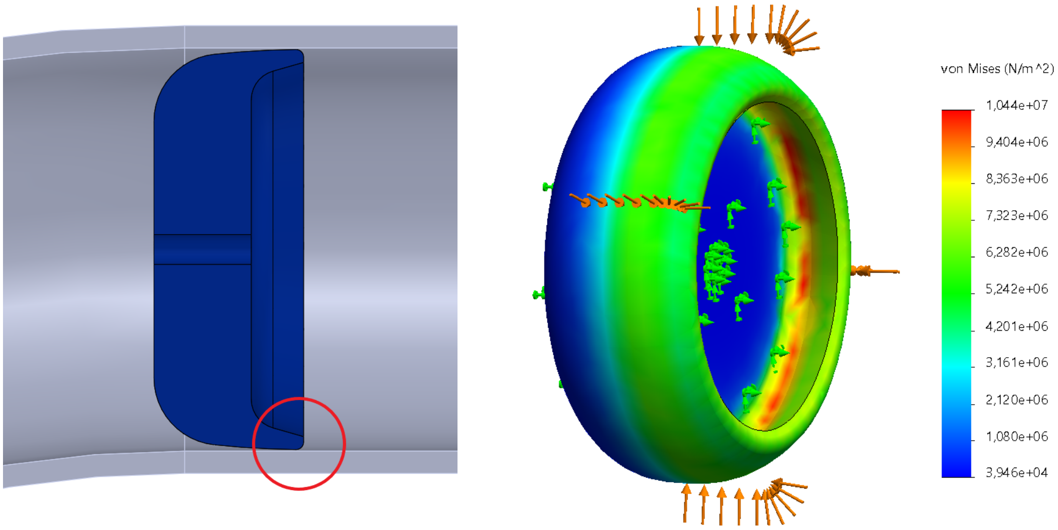
The initial mandrel design will inevitably have flaws, weaknesses, and features to improve, however, it is a good starting point for developing a mandrel that can offer the support needed for bending.

Advantages

- The mandrel is flexible.
- The mandrel has the degrees of freedom (DOF) needed from customized bending.
- The metal rod fixation method is quick and easy, with a bolt to fasten.
- The head connector fixation to the metal rod connector is strong and leaves a steady connected part.

Disadvantages

- The wire fixation method is unreliable in both ends, as one end is fixed to the bolt while the other is tied to a nut and tightened with washers. This leaves an unreliable fixation that at the bolt is either prone to complete break off, or at the mandrel tip where the nut can loosen and fall off at enough force.
- The amount of chain links can be seen as excessive, as the effect subsides the further into the already bent tube they are located.
- The chain links are designed in a way that results in a lot of stress concentration in the whole outer perimeter of the link. Figure 19 shows the red circle, where, during bending, the stresses will be very high making the component very prone to fracture or complete break-off.



(a) Cross-section of chain link with weak point

(b) Simulation when forces act upon edge

Figure 19: Chain link design.

4.2 AM flexible mandrel: iteration one

This mandrel design is based on the analysis and evaluation of the initial mandrel design. From discussion and later discovery, a plural of improvements have been made, which will be presented in the following chapter.

4.2.1 Dimensions and components

The chain links have been changed to have rounded edges and an overall round circumference. This is to combat the singularities created by the contact force in the contact surface with the tube's inner face. The chain links are designed to have a tangential point with the tube at the center in the axial direction. At this location, they have a 0.2mm clearance to the tube's inner face. Increasing the roundness ensures that there are fewer stress points present when the tube is being bent at a steeper angle.

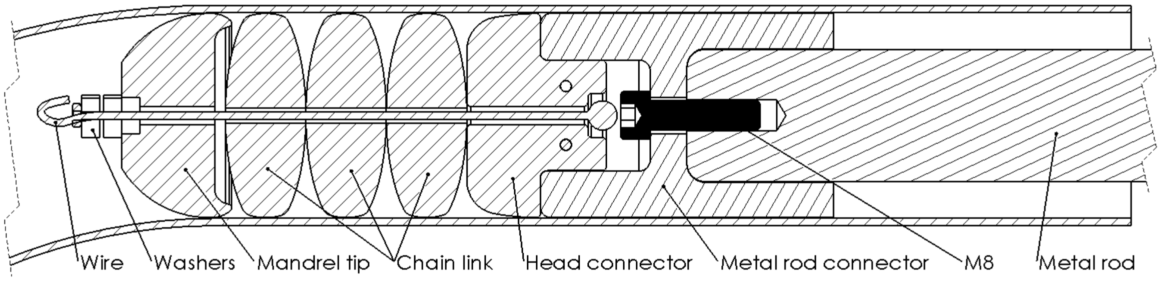


Figure 20: Cross-section of second mandrel design.

4.2.2 Mandrel assembly

This mandrel iteration has the same assembly process as the initial mandrel, as the component composition is the same. However, the wire solutions have been changed to a more durable thin cable, and the wire stopper is a permanent solution with a loop that can not go through the chain link center holes. This is accomplished by having a thin double-ended loop of steel wire and assembling it by pulling it through the center holes. When the flexible part is connected, the loops are opened with steel thimbles which fixes the wire in each end, stopping it from falling out. The mechanism is pictured in figure 21 below.

Figure 21: Thin steel wire with thimbles.

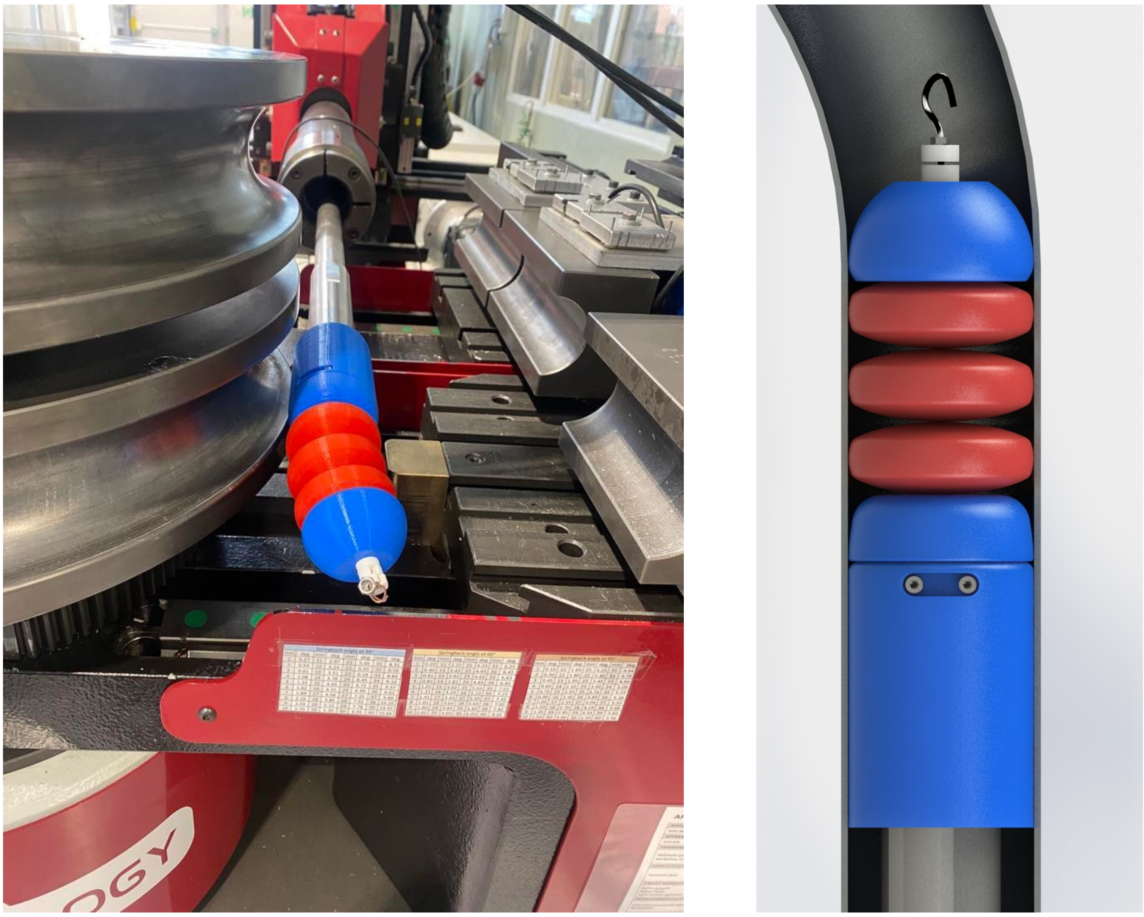
4.2.3 Advantages and disadvantages

Advantages

- The mandrel is flexible
- The mandrel has the DOF needed for customized bending

Disadvantages

- The fixation method is still not optimal, as the suggested method was not implemented yet. The chain link is therefore still connected to the next with a wire, which leaves room for much uncertainty when it comes to the tightness and fixation of the chain links.
- The chain links are not rounded enough, making it more prone to fracture or break off, as well as the possibility of getting stuck in the tube.



(a) Assembled mandrel in RDB

(b) Mandrel design render

Figure 22: Iterated design two.

4.3 AM flexible mandrel: iteration two

4.3.1 Dimensions and components

For the second iteration of the mandrel, the circumference of the mandrel chain links was rounded out even more. The cross-section in figure 23 shows three chain links in the mandrel with a mandrel tip. However, it could be possible to remove the mandrel tip, as it doesn't measurably contribute with excess support this far out in the bend with the rounded tip, relative to the regular chain links.

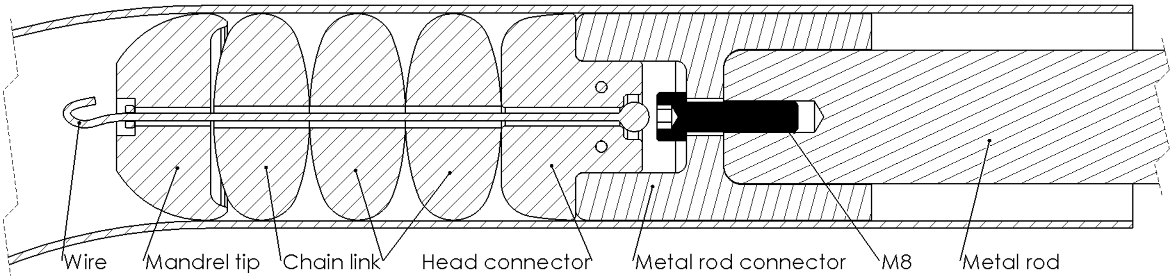


Figure 23: Cross-section iteration two.

4.3.2 Mandrel assembly

The assembly of the mandrel is identical to the two previous assemblies as they have the same general setup and flexibility. As well as the same wire connection is the same as in the previous iterations.

4.3.3 Advantages and disadvantages

Advantages

- The mandrel proves flexible for the bending of small and large angles.
- The mandrel has the DOF needed for customized bending.

Disadvantages

- The fixation method is still not optimal, as the suggested method was not implemented yet because of the availability of small enough wire loops. The chain link is therefore still connected to the next with a wire, which leaves room for much uncertainty when it comes to the tightness and fixation of the chain links. This fixation method also leaves room for considerable amounts of friction at each connection point, and can with a lot of usage lead to much wear and tear.
- The chain links are not rounded enough, making it more prone to fracture or break off, as well as the possibility of getting stuck in the tube.

4.4 Metal core with adaptable outer skin: initial design

The metal core mandrel is a flexible mandrel with a metal core in the center, with the possibility of attaching different diameter AM chain links in the outer perimeter. This makes the component compatible with all diameter tubes, as long as the diameter is below a certain size. The metal mandrel with core and chain links, as seen in figure 24, has been designed and developed at NTNU. This is the base design for the mandrel that has been developed later. The machine drawings of the parts produced at NTNU are found in Appendix A and B.

As the mandrel is designed and developed with conventional manufacturing techniques, it is rigid and only able to accommodate and support one singular diameter of tubes, unless all the parts are replaced with others. it is in need of changes and improvements to accommodate the different diameters of tubes it should be able to bend.

4.4.1 Dimensions and components

The current metal mandrel is dimensioned for a tube with an inner diameter of Ø58mm. The dimension of the chain link is designed in a way that is optimized for a component made of metal; sharper corners and a slacker arch at the tube tangential point.

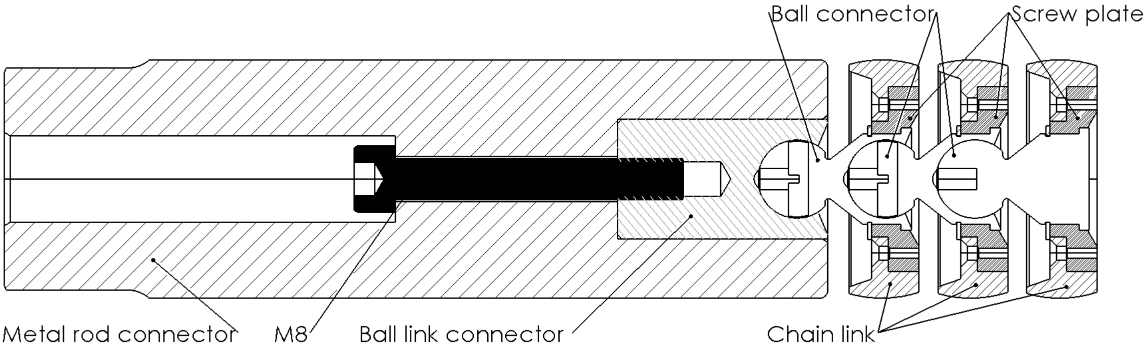


Figure 24: Cross-section of metal core mandrel.

4.4.2 Mandrel assembly

The assembly of this mandrel is done by connecting one and one chain link to a screw plate with three bolts through the two components. Then one ball connector is put through the screw plate and fixated with a retaining ring. Then the other ball connectors are assembled in the same way. When all the flexible parts are connected together, the last ball connector is placed in the ball link connector and put into the metal rod connector, and screwed into place with an M8 bolt. The flexible metal mandrel is now assembled and ready to be screwed onto the RDB metal pole.

4.4.3 Advantages, disadvantaged and improvements

Advantages

- The mandrel proves a secure and durable metal core.
- The mandrel has the required DOF.
- Fixation to both the flexible chain links and the metal pole is quick and easy.

Disadvantages

- As the metal mandrel is rigid, the current setup can only accommodate one singular diameter.
- The chain links are designed in a way that can only be produced in metal, compared to if it was printed with other weaker material, which would leave the component weak and prone to fracture.

Improvements

Taking base in the design of the mandrel as it is, but changing it to accommodate different tubes of different diameters we must change the design substantially.

- Change the metal rod connector to a smaller diameter so that there is space for a PLA cover.
- Making a fixation method for the metal rod PLA cover to be fixated forwards and backward in the axial direction.
- Change the current chain links to one of PLA, with a design that works with PLA. Meaning, rounder, and not as sharp corners.

4.5 Metal Core with Adaptable Outer Skin: Volum 2

The second and final design of the metal core PLA mandrel is developed using the improvement points from the metal core mandrel design. With the changes performed on the metal components, and the printed PLA parts, the design can now accommodate multiple diameter tubes, with a quick AM of new PLA chain links and a new PLA rod cover.

4.5.1 Dimensions and components

As seen in figure 25, the chain links have been improved for PLA material by rounding the edges and the outer perimeters. This is to combat the singularities created by the contact with the tube's inner surface. The chain links are designed to have a tangential point with the tube at the center in the axial direction, just as the initial chain links were designed. At this location, they have a 0.2mm clearance to the tube's inner surface. The roundness of the chain link leads to fewer stress singularities when the chain link is at a steep angle. The PLA rod cover is designed with the same clearance and with the chain links, with a 0.2mm distance.

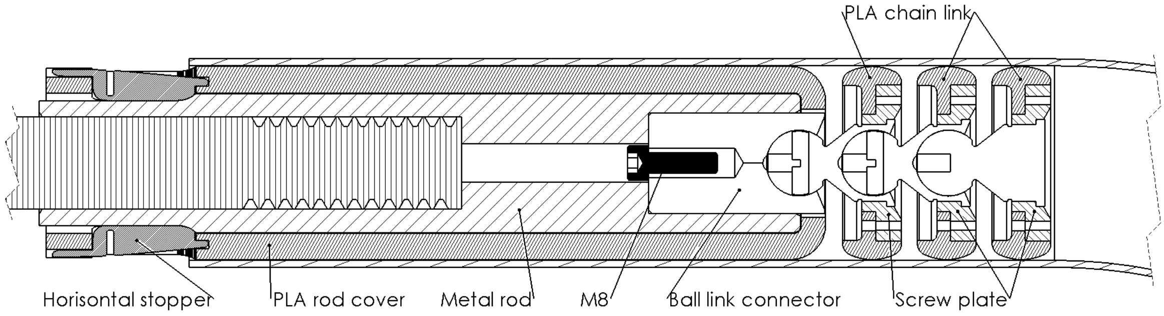


Figure 25: Cross-section of metal core mandrel with PLA shell.

4.5.2 Mandrel assembly

When assembling this mandrel, most is done as in chapter 4.4.2. The PLA rod cover is put on from the top of the metal rod. The tip of the metal rod by the ball link connector stops the PLA cover from displacement horizontally to the left, and the horizontal stopper stops the PLA cover from displacement to the right. The horizontal stopper works by being tightly wedged into the two holes at the back tip of the PLA rod cover, pushing down at the divot on the back end of the metal rod as well as being pushed down by the tube wall. This forces the PLA rod cover backward while being limited by the front of the metal rod. When these components are placed, the ball link connector with chain links is ready to be put into the metal rod and fixated with an M8 bolt.

4.5.3 Advantages, disadvantaged and improvements

The developed mandrel is a bi-product of a well-used and very optimized metal mandrel that performs well during bending. The changes made are therefore minor, and only to accommodate for different tube diameters and the fact that the components are produced in PLA.

Advantages

- The rod is flexible and has the needed DOF for tube bending.
- The metal core offers a strong and resistant connection.

Disadvantages

- Fixation in the axial direction is dependent on the horizontal stopper. Tests have yet to show whether the solution is durable and trustworthy.
- PLA chain links have yet to show if they are resistant to the forces they are subject to during bending.

Improvements

The main design of the mandrel is rather optimized. However, the weak link is the horizontal stopper and can be the point of failure if it breaks, as this will displace the PLA rod cover to the right during bending and the support will not be in the tangential bending point anymore.

(a) PLA chain link and screw plate assembled, and ball connector

(b) Flexible PLA mandrel

Figure 26: Metal core mandrel with PLA shell prototype.

4.6 Material choice

From the pre-thesis, it was concluded that the material used was more than sufficient enough to withstand the forces and stresses present during testing. The same material is therefore used in the continuation of the master's thesis, and it is identical in all the components produced.

The material used in the FFF was Polylactic acid, PLA, in differing colors. The most relevant technical specifications of the material are shown in the table below.

PLA		
Property	**Value**	**Unit**
Young's modulus	2.3 ± 0.1	GPa
Tensile yield strength	37.6 ± 4.0	MPa
Elongation at yield	1.9 ± 0.3	%
Impact strength Charpy	5.0 ± 1.4	kJ/m ^{2}

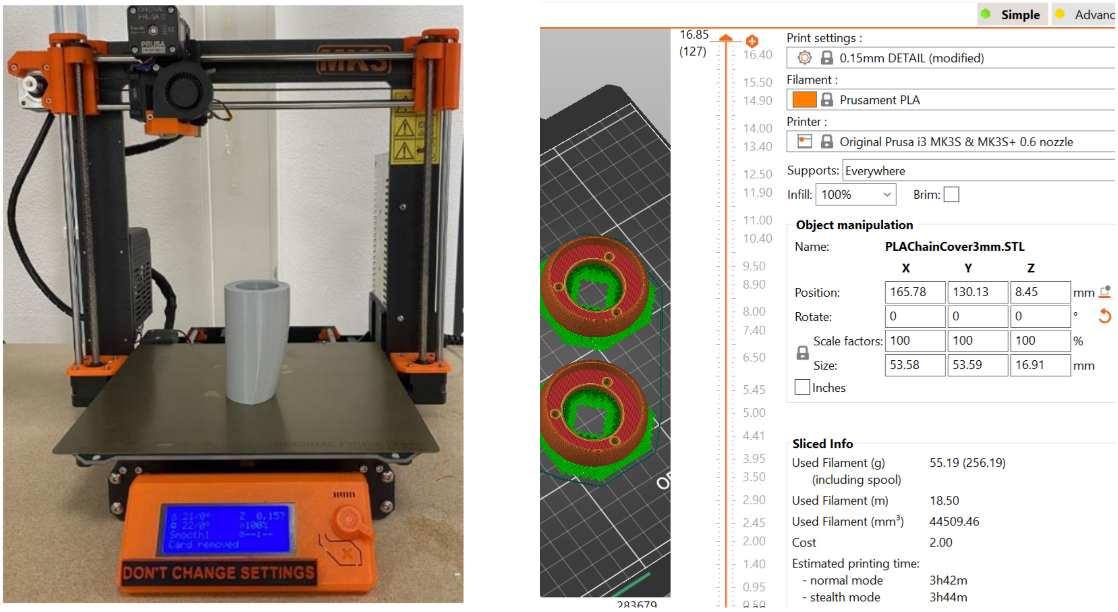
Table 3: Material properties of PLA (Prusa 2018).

4.7 Additive manufacturing and assembly

After designing and developing a solution in a CAD-software, in this case SolidWorks, the next step in the rapid prototyping process is to print and conduct any after work needed. The printers used are of the brand Prusa MK3 and MK3S+, with 0.6- and 0.4mm nozzles, which are all standard fused filament fabrication (FFF) printers, and print fast and effectively.

The parameters used for the printing of the different parts are selected to give the strongest and most durable components with a sufficient surface finish. The infill of the product, meaning the amount of fill that should be inside of the grid in the shell is chosen to be as high as possible, 100% infill. The layer thickness is also set to the lowest possible, to ensure the smoothest surface finish. This produces a solid part that ensures the highest resistance to yield stress from the testing, for the given material chosen with the identified material properties.

The parts are rounded on the edge to mitigate any possibility for singularities in stress while bending, and during printing, it is therefore often necessary to support both under and around the part to ensure the correct printing. The printed parts are therefore often in need of some after work by removing the supports present. Depending on how the supports are added, this can occasionally lead to uneven outer surfaces of the part. However, the location of the supports is isolated from the tube contact surface and does not result in a significant reduction in performance because of surface defects.



Print settings : 0.15mm DETAIL (modified)

Filament : Prusament PLA

Printer : Original Prusa i3 MK3S & MK3S+ 0.6 nozzle

Supports: Everywhere

Infill: 100%   Brim: ☐

Object manipulation

Name: **PLAChainCover3mm.STL**

	X	Y	Z	
Position:	165.78	130.13	8.45	mm
Rotate:	0	0	0	°
Scale factors:	100	100	100	%
Size:	53.58	53.59	16.91	mm

☐ Inches

Sliced Info

Used Filament (g) (including spool)	55.19 (256.19)
Used Filament (m)	18.50
Used Filament (mm^3)	44509.46
Cost	2.00
Estimated printing time:	
- normal mode	3h42m
- stealth mode	3h44m

(a) 3D-printing of mandrel links

(b) Printing parameters

Figure 27: Addictive manufacturing in real time.

5 Experimental results

5.1 Rigid mandrels

The results from the project thesis have been important for the master and are of great value, as they set the ground and can show that it is possible to continue further work within the field. The test was then conducted with a metal mandrel, AM rigid mandrel, and AM rigid mandrel at different extensions from the tangential point. The results can be seen in the graph in the chapters below, depending on the different extension angles.

5.1.1 Rigid mandrels: 0mm, 5mm, and 10mm extension

During bending with extension distances of 0mm, 5mm, and 10mm, there are obvious trends in the graphs. From figure 29 it can be observed that the metal mandrel offers the best amount of support and is the top performer. However, when comparing the rigid AM mandrels to the rigid metal mandrel, it reveals that the AM mandrel is not far behind, reducing the support of the whole diameter of the cross-section with only approximately 1mm.

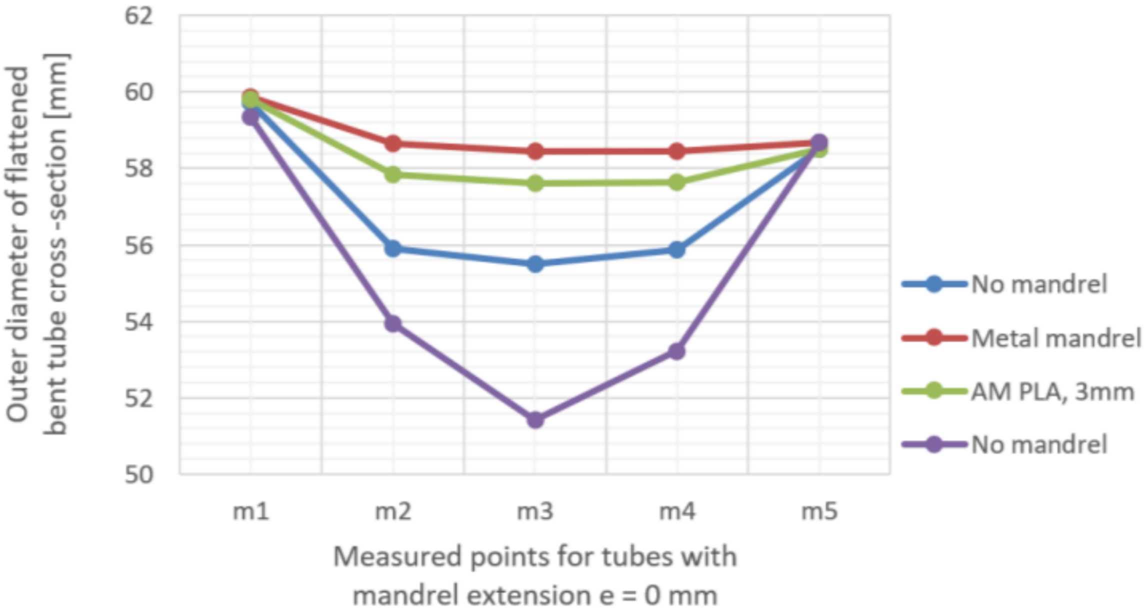


Figure 28: Rigid mandrels with 0mm extension.

5.1.2 Rigid mandrels: 3mm wall thickness tube

From qualitative results on different tubes, it can be concluded that a wall thickness of 3mm and the tube itself provides good support when being bent, as there are little to any visible defects like wrinkling or cracking. However, from quantitative measures, like in figure 29, the graph clearly shows that the tube flattening is significantly reduced when introducing a mandrel. Here it can be seen that the rigid PLA mandrel performs on top when the extension is e=10mm, superior to the metal mandrel even.

This implies that the positioning of the mandrel tip, in relation to the tangential point is of high importance to get the most optimal results during bending. However, when comparing the rigid metal mandrel to the rigid PLA mandrel at the same extension distance, the metal mandrel comes out on top. This confirms that the PLA mandrel, because of its softness and weaker mechanical properties will not provide the same results as the metal mandrel, even though the error is rather small.

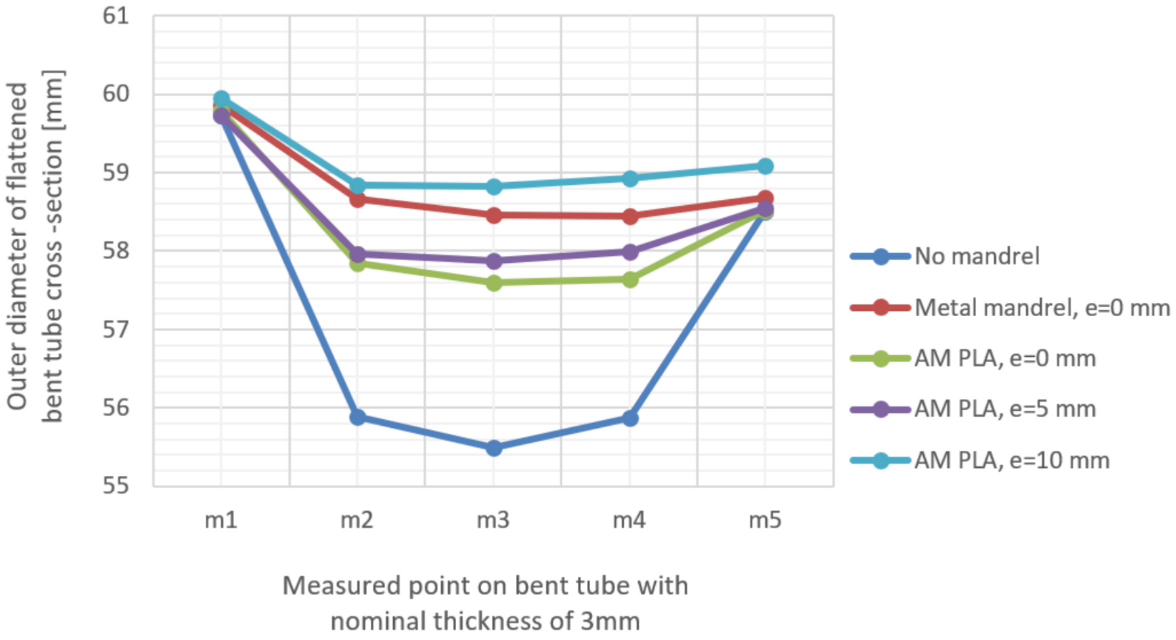


Figure 29: Rigid mandrels on 3mm tube.

5.1.3 Rigid mandrels: 2mm wall thickness tube

A 2mm wall thickness tube is evaluated to be rather weak when it comes to supporting itself during bending. Bending without a mandrel will therefore lead to a significant amount of wrinkling, which can be observed both qualitatively and quantitatively. From the graph in figure 30 the mandrel, with an extension of e = 5mm, can be observed to significantly reduce the flattening, nearly 5mm. Likewise, with an extension of 10mm, it can be reduced by approximately 6mm. Qualitative measures when looking at the bent tubes can also reveal that there is an almost complete mitigation of wrinkling and cracking when adding the rigid PLA mandrel.

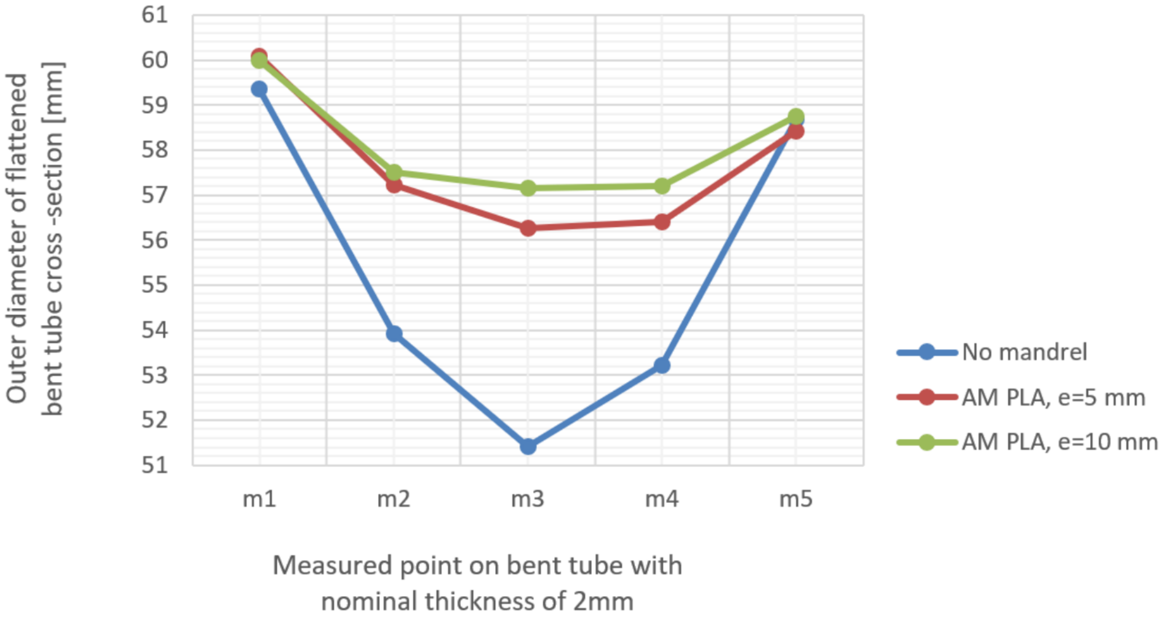


Figure 30: Rigid mandrels on 2mm tube.

5.2 Flexible mandrels: PLA core

5.2.1 Initial design

The first iteration of the mandrel design did not go through tests. Through discussion and physical evaluation, it was determined to be in need of too much improvement and changes to be able to perform at the necessary level. Points such as the curvature of the chain links, fixation method between each chain link, and friction between each chain link, were features that needed improvement.

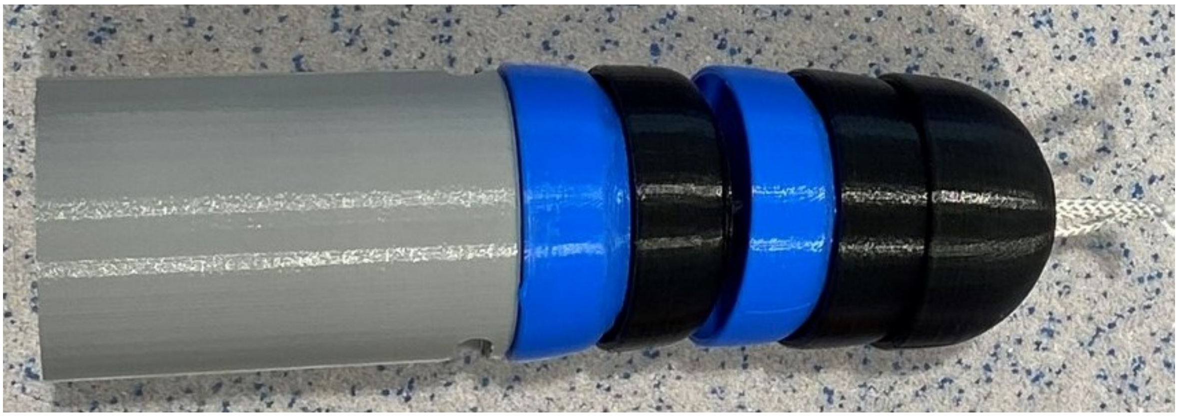


Figure 31: Initial mandrel design.

The evaluation and assumptions that support not going through with tests are shown in the list below:

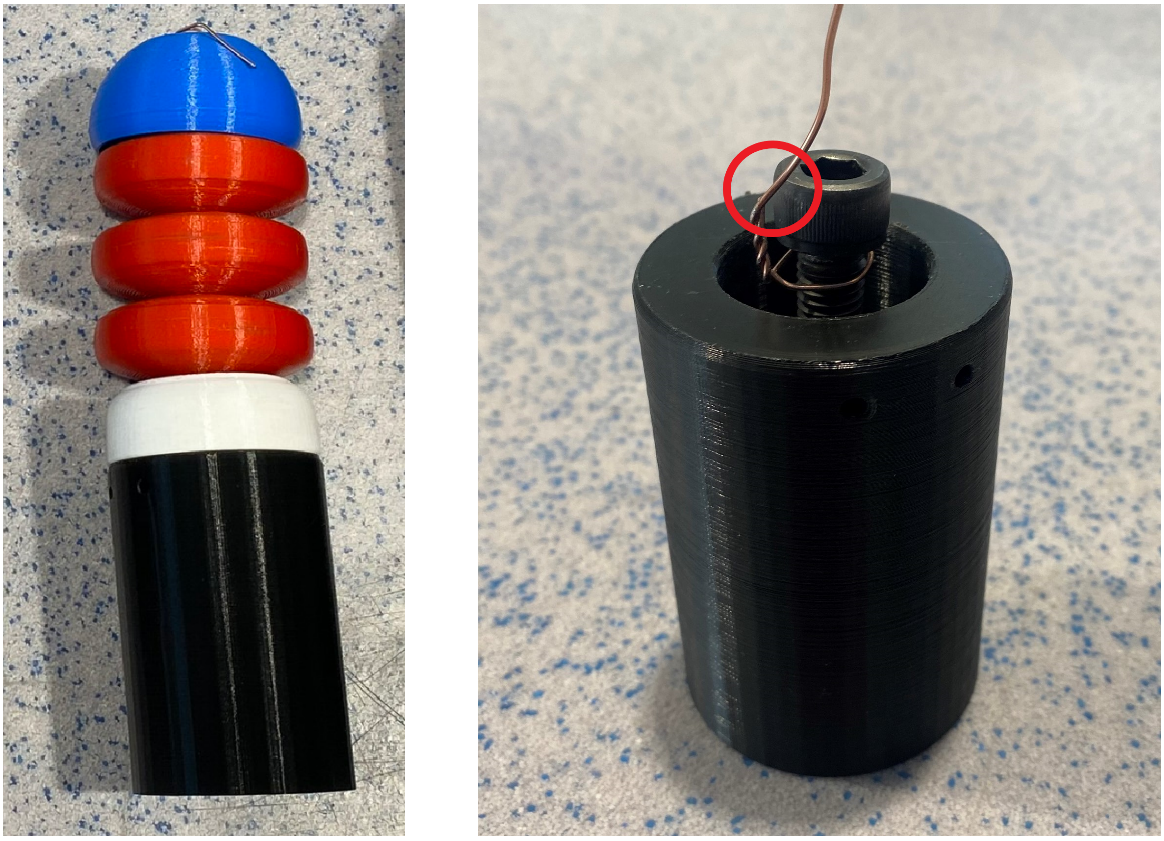
- Chain link curvature is too flat on the top. This leads to support only when the tube is unbent because there will be more contact surface. When the tubes go through bending however, the chain link curvature will only be in contact at the corners, which leads to a more concentrated load onto the inner surface of the tube. This type is concentrated load will also lead to stress singularities on the edge of the chain link, as discussed in chapter 4.1.3, and can lead to defects or worst case cracking or rupture on the AM chain link edge.

- The fact that each chain link is resting on the previous chain causes a significant amount of friction between the links. This decreases the smoothness of the movement and rotation and causes unnecessary wear on the links when in use.

- The fixation method between the metal rod connector, head connector, and chain links is in this design a thin rope. The rope is evaluated to be too fragile and weak to be able to hold the components together during a bending process with this amount of force acting on it.

5.2.2 Iteration one

The first iteration of the initial design went through a test in the RDB machine, however with unsuccessful results. In the middle of the bending process, the fixation method from the movable parts broke, leaving chain links stuck in the bent section of the tube.



(a) AM printed first mandrel iteration

(b) Red ring around wire fracture

Figure 32: Connection of wire to bolt.

Points of failure:

- The wire fixation, as seen in figure 32 (b), shows how the wire is fixated to the bolt. The wire is spun around to tighten around the bolt, which leads to the wire being pre-deformed before it is subject to large forces during bending. The assumption is confirmed, as this is where the wire broke during bending.
- During the bending, the results suggest that the chain links staggered inside the bent section, as one chain link got stuck in the tube after the breakage of the wire.
- The pre-made washers did not withstand the forces they were subject to during bending, and broke off. This created a slack in the wire that resulted in a chain link assembly with considerably much space between each link, which causes tension in the wrong places during bending.

5.3 Flexible mandrels: Metal core with AM cover

5.3.1 2mm wall thickness tube

The testing of the 2mm wall thickness mandrel was done on six different tube specimens, as stated in the test overview in table 2. The description of them is T1, the first test, till T6, the last test. The flexible mandrel was positioned in the tangential point of the bending, to begin with, but also slightly adjusted to optimize the bending.

The results and experimental data from the test are presented in figure 33 below, and can show the gradually decreasing cross-sectional flattening of the tube with each test of the specimens. Overall, the last specimen, T6, has the most consistent cross-sectional diameter, with T3 coming in second.

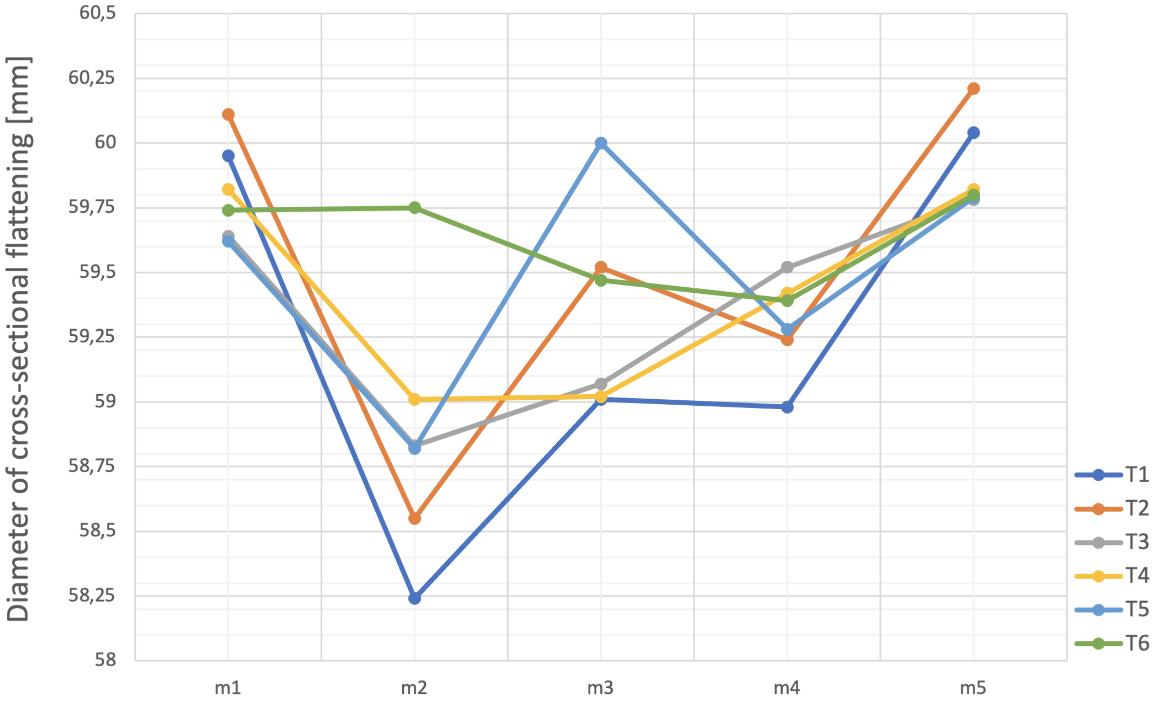


Figure 33: Rigid mandrels on 2mm tube.

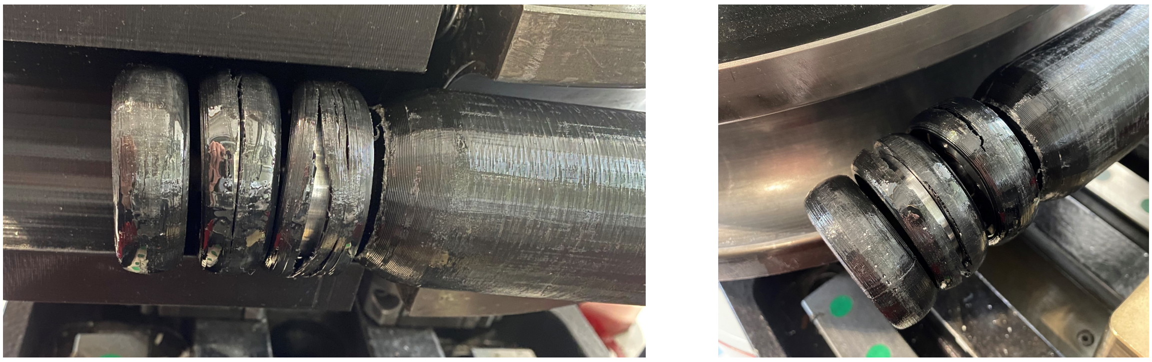
The reason behind the gradual optimization of the flexible mandrel on each of the specimens is because of the change in the parameters of the RDB machine. Given the sub-optimal results on T1, with considerable amounts of wrinkling on the intrados and wear on the extrados of the tube, the solution has been to change the RDB parameters to counteract these defects.

Figure 34 reveals no major difference quantitatively between the different tubes, however, it is possible to observe a slightly smoother surface on specimen T6, as well as T3. The smoothness is a byproduct of an increase in the mitigation of wrinkling defects and comes from the mandrel being improved support for the tube during bending for every test specimen.

Figure 34: Specimen T1 (top) - T6 (bottom).

5.3.2 Chain link damage

Already during the bending of the T1, the first specimen, there could be heard cracking during bending, and later observed severe cracks in the flexible mandrel chain links. The damage is observed in figure 35, where the extent and significance of the cracks can be seen. The two chain links closest to the rigid mandrel are affected hardest, while the chain link closest to the free end is rather untouched. The rigid mandrel has also experienced trauma on the top, the surface towards the chain link, as seen in figure 35 (a), and can be a sign of the chain link in front rubbing and wearing on the mandrel. The high contact pressure and inwards pressure because of the flattening of the tube, leads to high pressures on the chain link, causing them to crack.



(a) AM printed first mandrel iteration

(b) Red ring around wire fracture

Figure 35: Connection of wire to bolt.

5.4 Mandrels: rigid vs. flexible

5.4.1 Comparison of rigid, flexible and no mandrel tubes

After testing, evaluating, and measuring the different specimens from the test during this study, as well as the previous study, we can see a tendency in the graphs. In figure 36 the tube tested with a rigid AM mandrel from last semester is compared to the two top-performing flexible mandrel tube specimens, and lastly, a tube bent with no mandrel at all. The graph clearly shows that the tube bent with no mandrel at all, has the highest amount of cross-sectional flattening, with decreased values as high as 1cm in diameter. To somewhat of a surprise, however, is the fact that the AM rigid mandrel is the second-best performer. The cross-sectional flattening with the rigid mandrel is approximately 5mm, which while being a significant amount, still indicated that it is of large support during the bending.

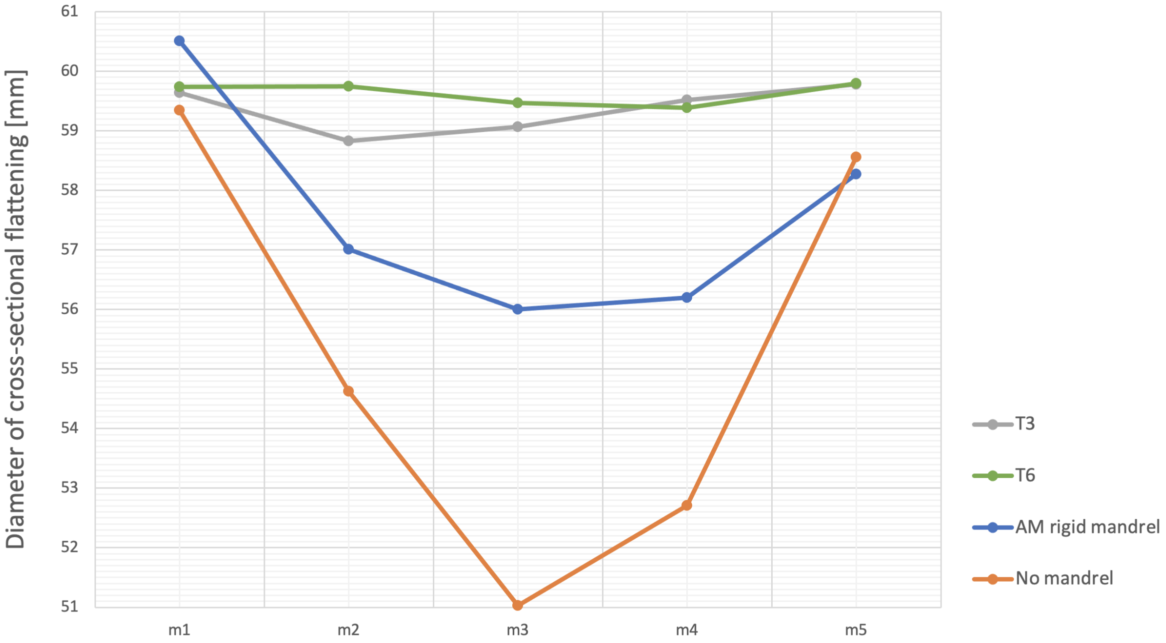


Figure 36: Rigid mandrels on 2mm tube.

However, out of the three cases the flexible mandrel comes out on top in the tests. Bending with a chain link mandrel reveals that the cross-section holds a significantly truer form, with a difference of as high as 3.5mm, compared to the diameter of the AM rigid mandrel tube. This suggests that the flexible AM mandrel is of significant support during bending, but mostly that it can offer additional support to the tube even after the bending has occurred in the tangential point of the RDB.

In figure 37 below, the results from the graph below can be seen qualitatively through observation. The figure can show the two best-performing test specimens, T3 and T6, from the top, and the 2mm AM rigid mandrel, to the no mandrel bent tube on the bottom. The figure can clearly shows that although the two flexible mandrel specimens suffer from a significant amount of wrinkling on the intrados of the tube, the flexible mandrel can offer significantly more support both during and after hitting the bending point. This is seen from above by the thickness of each tube at approximately 45°into the 90°bend, and how the T3 and T6 are thicker than both the AM rigid mandrel tube and no-mandrel tube. This effect is because of the increase of contact pressure between the mandrel and inner surface that goes up because of more surface area touching the tube after the bend point, which leads to more support when the tube is of nature trying to flatten out again.

Figure 37: Rigid mandrels on 2mm tube.

6 Discussion

6.1 Rigid mandrel: metal vs. AM

Using the qualitative and quantitative results collected from the experimental tests conducted, as well as the qualitative data from observation, we can see a definite and clear pattern in the results. The expectations prior to the study, acquired from both literature and studies done in the field, have been that the AM mandrel will perform well, however to what extent has been uncertain. For further research and data collection, the results from this study are of high importance.

The results from the tests on the 2mm and 3mm tubes can present that the metal mandrel set a definite threshold of very high mitigation of all defect a tube will be subjected to during bending. The cross-sectional flattening and wrinkling are decreased to only measuring a few millimeters, although this is to expect given the material and mechanical properties of steel mandrel set up against an aluminum tube. Nonetheless, the AM mandrel is not performing much worse. Against a tube bent without a mandrel, the AM mandrel can provide support up to an increase of almost 2cm in diameter.

Although the rigid AM mandrel was able to prove itself very well during tests by reducing flattening on a fundamental level, it was also observed that it can be further optimized by changing the extension distances from the tangential bending point. Increasing the distance from 0 mm to 5- and 10 mm showed an increase in the test results the higher the extension was. Although a higher extension than 10mm was not tested, this is expected to be closing up to the maximum extension distance limit.

Lastly, the operational defects on the AM mandrel are of high importance. The scraping and visible wear and tear on the mandrel are certainly present, as expected from a material that is of a significantly softer nature than metal and has weaker mechanical properties. The increase in extension distance does also force more contact pressure onto the outer surface of the mandrel tip, which leads to more expectancy of surface defects. However, despite the surface defects and wear, the mandrel is yet to show more significant signs of degradation such as cracks or fractures.

6.2 Flexible mandrel

The development of the flexible mandrel is done to give a tooling that can offer more support than a regular rigid mandrel. It gives the tube support of the cross-sectional area even after the bending has occurred in the tangential point, as the chain links are located forwards of the point. The first samples from the experimental testing were largely wrinkled and somewhat damaged on the outside surface from the pressure die, but after minor tweaking and change of parameters on the RDB machine, the results were much more optimal. Towards the last sample, the machine was somewhat tuned and the result of the last specimen came out decent. The state of the mandrel chain links, however, was not optimal at all. Already after the first bending session of the first specimen, the mandrel chain links experienced fracture and cracking, and towards the last test were almost completely broken off, as seen in the pictures from chapter 5.3.2. The main problems and possible solutions to the degradation are presented in the chapters below.

6.2.1 Mandrel degradation

The main defect the mandrel chain links were subject to was cracking, with the first instance happening already at the test of the first specimen. Out of the three chain links on the mandrel, the two closest ones to the mandrel experienced the largest force. This could be due to the fact that the chain link close to the free end has the possibility of free movement, as it is not as restricted as the two prior links.

Contact pressure and forces

However, the main reason as to why they experienced such major degradation is believed to be the high contact forces that come from the tube flattening, as well as a too-tight clearance to the inner diameter of the tube. The clearance is 0.2mm in radius from the outer surface of the chain link to the inner surface of the tube. This can lead to too much surface pressure, which results in the cracking of the links. Increasing the contact forces because of the tube flattening also leads to a major increase in the radial inwards working pressure on the chain link.

Infill percentage and pattern

Another possibility that can be the source of the cracking and defects can be related to the infill percentage and infill pattern of the chain link. The parts were printed with a 100% infill density which means a ”pattern-less”-pattern as it is just printed back and forth till completion. This can lead to a part that has built-in stresses or residual stresses in the parts even before any pressure has been applied to the parts. It could therefore be beneficial to study whether or not the chain links would perform more optimally with less infill and a different infill pattern, because of the possible increase in component strength and durability.

Printer setting and material choice

Changing the production facility to a different printer could also be a possible solution. A printer that has a thinner nozzle would be able to print the wanted component with higher dimensional accuracy and thinner layers. This could lead to a component printed with that actual clearance between the chain link and tube, which is needed so that the parts have enough surface to support the tube, but without being too large for the tube. Printing with a different material than the standard PLA filament could also be a large benefit. PETG could be a good competitor, as it offers higher strength and greater durability. It is also more flexible than materials such as PET and PLA, which is an important benefit especially during printing, as it prevents the produced component from becoming brittle after printing.

6.2.2 RDB machine parameters

During this bending process, as opposed to the bending that was conducted in prior runs, like the pre-thesis experiments, the RDB machine has been a factor as to why the results have been sub-optimal. Other studies have also been conducted on the RDB, and parameters have been changed and therefore not consistent throughout the whole study. This could be a major factor as to why the mandrel chain links went through such high degradation during bending, and also why the wrinkling was so significant compared to prior experimental testing. The cross-section of the RDB in figure 12 shows the different components discussed in the chapter.

One of the parameters changed has been the distance the pressure die has followed the tube through the bending process. The distance of this following implies whether or not the tube is been stretched too much or not. With a long following, the tube is not being held in place as long, resulting in more wrinkling during bending. When the pressure die follows the tube for a shorter distance, the wrinkling is mitigated more as the material on the intrados is stretched out because of the holdback of the pressure die. Lastly, the mitigation of the wrinkling can possibly be accomplished through the installation of a wiper die, as this is a component that is not present on the RDB machine at the NAPIC lab today. The wiper die is a component with a thin feathered edge that has the main job of mitigating wrinkling. This is done by forming pressure around the intrados of the tube right before the bending at the tangential point takes place. The pressure counteracts the accumulation of material that forms and the wrinkling is therefore largely or fully mitigated.

7 Conclusion and way forward

7.1 Conclusion

Having had to design tooling by coming up with something novel, in a field where the research has been rather limited, has been a challenging yet extremely rewarding experience. The possibilities have been many, and while some designs have fallen through and not really proven themselves worthy, others have been a success. Through the challenges faced in the pre-thesis work, and the test and results that have positively surprised us in the process, it has been possible to take these solutions and continue the work into the master thesis. The rigid mandrel designed in the pre-thesis could be looked at as a success and finish line in the development, as the results were very satisfactory and optimal to serve the purpose of supporting during the bending process. However, in the spirit of always improving and finding ways to make a product better, further development of the product has only been natural. Therefore, the main motivation and goal of this thesis have been to find a way to improve the rigid mandrel in a way where the tooling can further support a tube being bent, and cater to different and a broader specter than just on singular dimension tube.

To see how the product has performed, a good measuring point has been the research questions identified in the beginning. Whether or not the study has been able to answer the questions or not, can show to what degree the product has been a success and where the possible improvement points are. The research questions with answers are as follows:

1. How can one design cost-effective tools for more customized tube bending processes?

Although we are not able to fully put a qualitative value on the comparability between a flexible mandrel in metal, and a flexible mandrel AM printed, we are able to read the results gotten from the test. Even though there were multiple iterations tried of the flexible mandrel, the end and most optimal result have come from the metal core AM mandrel. This has taken the basis from the design of a fully metal mandrel and developed and adapted it into being a functional hybrid solution between a metal mandrel and an AM mandrel. This solution has led to the fully metal mandrel becoming an adaptable solution that can be compatible with all different dimensions of tubes, with a quick change of the outer shell of the mandrel. Although this is a solution that takes an already existing metal core into use, it has been the superior design compared to other iterations designed in this thesis. Therefore, to answer the question of how one generally could design such a solution, it would be to take basis in a strong and durable metal core, and have shells and parts to connect onto the core. This offers a solution that is fully compatible with different dimensions, as well as strong and durable, and easily interchangeable. And as the production of this type of AM mandrel only demands a one-time complex conventional metal forming production of a metal core, compare to a fully metal mandrel, it is simpler, cheaper, and more resource-saving. Especially since we are able to use the simple procedure of FFF and cheap but functioning material filaments.

2. Can results from the test be used as a justification that other tools in the RDB process can be replaced?

Through experiments, results, and data collected from the test it is definitely possible to justify the replacement of other tools in the RDB process. Although the applicability isn't 100% transferable, the research provides a starting point for further replacement. The main focus area would initially be for components in the process that are assumed to need a replacement for each dimension of a tube if it would for example need a change in outer diameter. These are parts such as the wiper- and pressure dies. This could counteract the large costs and resources needed to produce the parts in metal, the conventional way, and have a large inventory of different components. Although the justification is there and the recommendation is to start replacement, it is still rather unclear the level of durability and resistance the parts have over time. This has not been fully possible to test yet, due to the limited amount of testing cycles the different parts have been subject to.

3. Are the methods used now applicable to processes when bending with higher-strength tubular materials such as titanium and steel?

As of now, with the current testing and data collected, I would classify the current state-of-the-art AM components as not yet applicable to higher-strength tubular materials. The current testing and data have been collected on aluminum tubes, which is a relatively soft material that is easier to mold. As the rigid mandrel experiences little to no serious wear, it could be tested with stronger more durable material, but the flexible mandrel however would need more improvement. As the chain links on the flexible mandrel suffered as much degradation as they did, it is possible that it would need to go through another design iteration to be more optimal and resistant to the high forces present in the process.

The research process started with the pre-thesis work of developing a rigid mandrel, testing and evaluating it, and concluding with it being a definite success. This has led to a product that can be further developed and tested and improved in a way that the mandrel is flexible enough to better support a tube. Through trial and error with different iterations of the flexible mandrel, with changes in both fixation methods and chain link design, it was possible to develop a design that can be of significant support to profiles during bending. This solution can be customized and easily changed to different dimensions, and well as it is highly cost- and resource-effective.

This thesis can contribute with data and performance reviews, as well as a design of a mandrel that has proved to be good and solid support. Although the design has not been able to entirely be able to solve the problem, as the chain links showed definite signs of damage and fatigue, it is clearly shown that the design has large potential and should be further developed and tested. How this process should continue is shown in the chapter below.

7.2 Way forward

Based on the results that have been collected in this study, both in the pre-thesis and the master I would consider it a definite possibility for further development and research in the field. With the little literature we have from before in the field of AM tooling for RDB, as well as generally in the field of metal forming, it is in need of further development and research. The results and data are very promising, although as mentioned before the need for durability and longevity assessment is needed to see if the process cost of producing AM components and tooling doesn't equal to the conventional manufacturing process of this tooling, although this is very unlikely due to the minimal cost of producing tooling through FDM. The performance tests and reviews must be done through continuous testing and development, as well as the possible replacement of other components in the RDB process, such as the wiper die or pressure die, to see whether or not it really can be applied in the long run.

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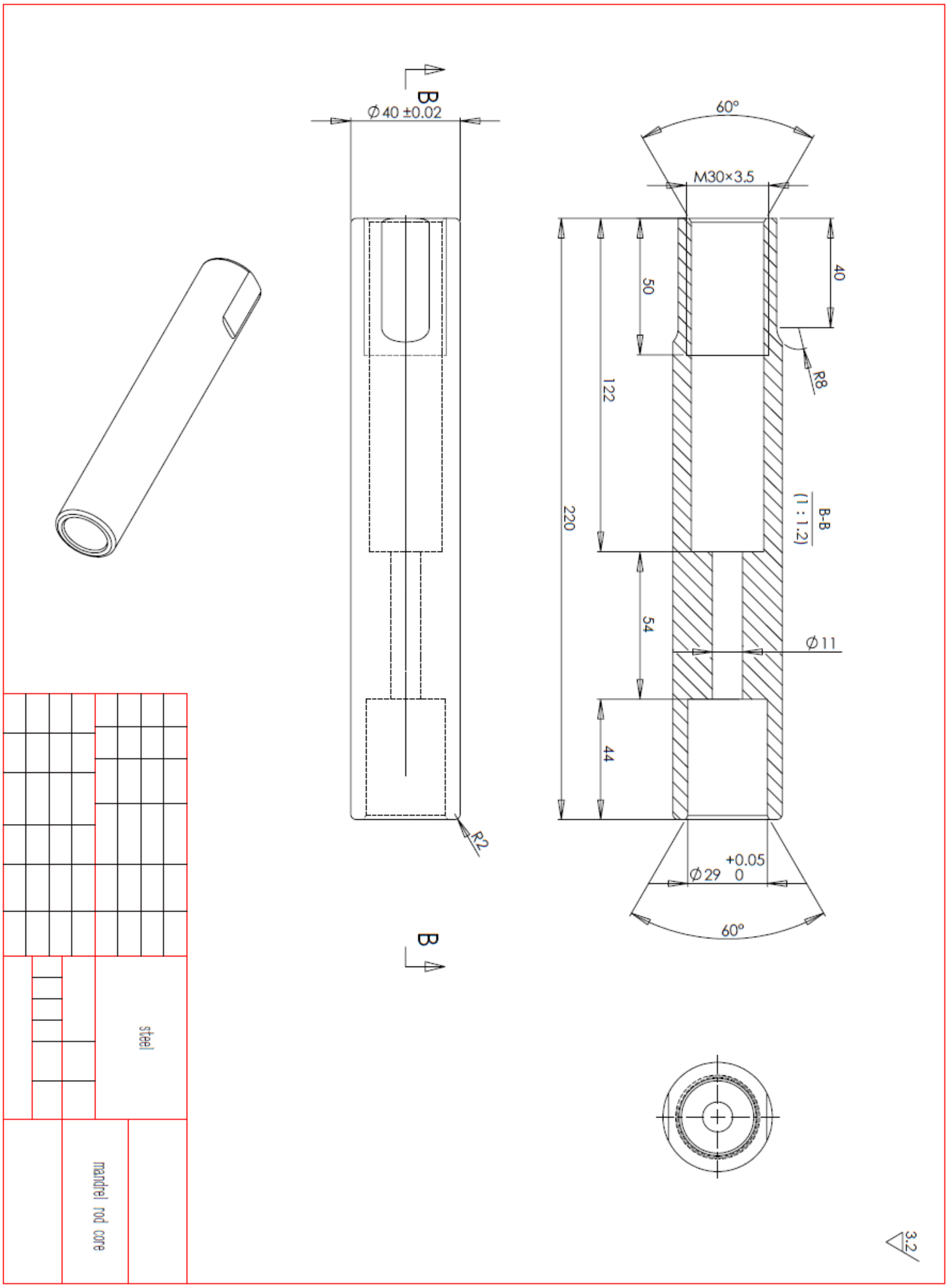
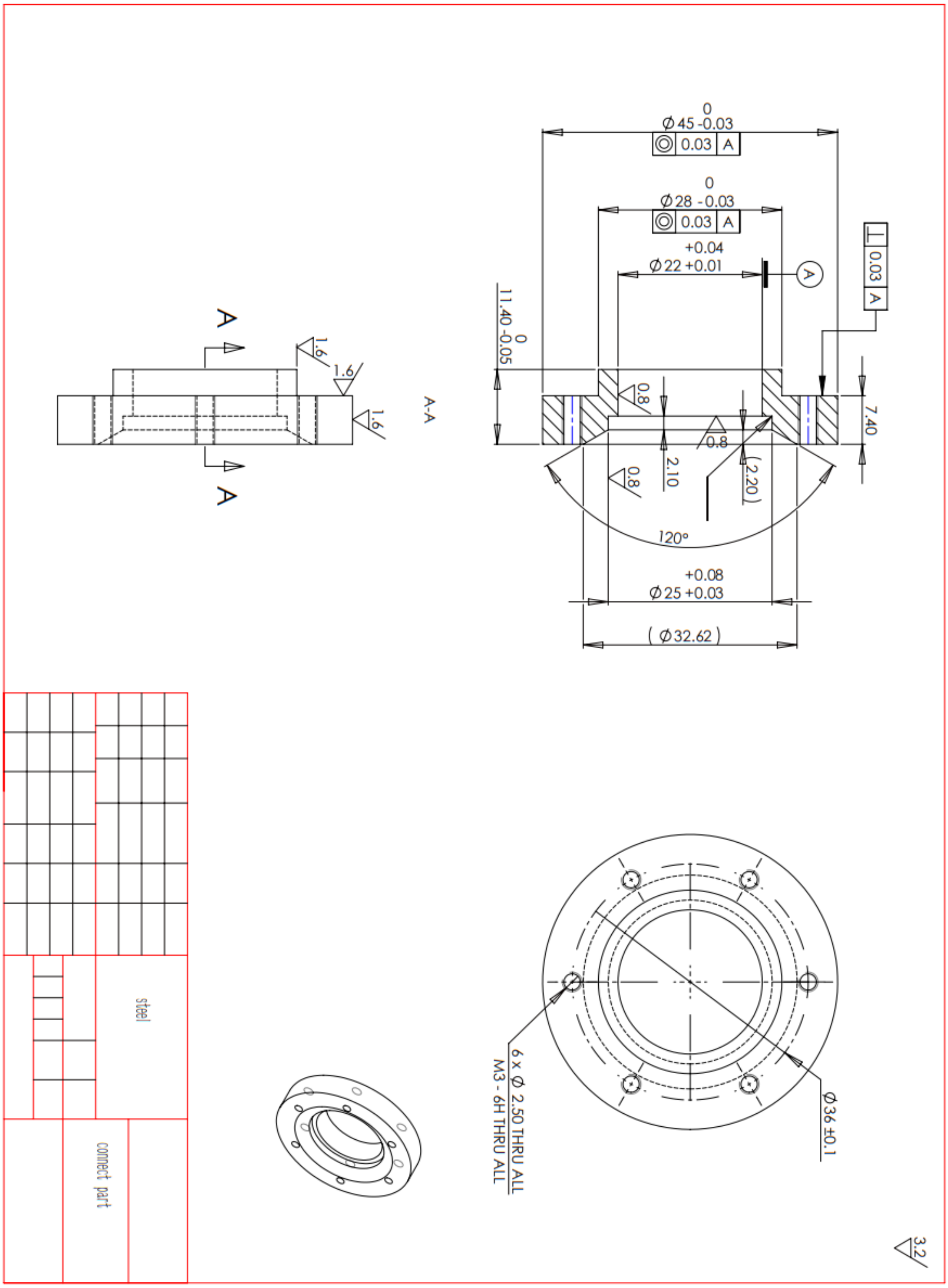
Appendix

A Metal Rod Connector Machine Drawing



B Screw Plate Machine Drawing



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