



CHALMERS



Single-step production of non-assembly mechanisms using additive manufacturing

A literature study for the development of design guidelines for micro-mechanisms using powder bed fusion - laser beam technology

Bachelor's thesis in the Department of Industrial and Materials Science

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Cover: Render of redesigned joints. From left to right; Spherical joint with cage
design, revolute joint with worm design, and helical joint with hemisphere design.

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Abstract

Non-assembly additive manufacturing is a manufacturing process that eliminates the need for assembly and joining, effectively saving time, costs, and processing whilst making it possible to create complex geometries. There are possible future applications for non-assembly mechanisms in several fields of engineering, such as expandable orthopedic implants in the biomedical industry, or weight- and volume saving constructions in the aerospace industry.

While previous studies cover various aspects of additive manufacturing, design criteria and redesign ideas for non-assembly additive manufacturing are yet to be explored thoroughly. Thus, this thesis delves into the subject through extensive research and literature studies, and a toolbox that provides these guidelines was created. The study is specifically targeted toward the production of micro-mechanisms using powder bed fusion - laser beam technology. To achieve this, several questions were raised: What types of micro-mechanisms are possible to produce using additive manufacturing and how can these be optimized for the technology? What is the most intuitive way to present the findings of the report?

The toolbox resulting from this study was built as an interactive HTML file to easily present the design criteria for each of the micro-mechanisms, along with examples of alternative designs. Lastly, prototyping in polymer with fused deposition modeling was conducted for proof of concept for the developed guidelines.

Keywords: Additive Manufacturing, Non-assembly, Powder Bed Fusion - Laser Beam, Micro-mechanism, Joints, Single-step Production, Redesign, Design Guidelines, Support Structures, Build Orientation

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List of Acronyms and Terminology

Below is the list of acronyms and terminology that have been used throughout this thesis listed in alphabetical order:

AM	Additive Manufacturing	A process of creating three-dimensional objects by adding layer upon layer of material. Commonly referred to as 3D printing.
CAD	Computer-Aided Design	The use of computer software to create, modify, and optimize 3D designs.
DfAM	Design for Additive Manufacturing	A design methodology where certain parameters of a product are optimized depending on the capabilities of additive manufacturing.
DfMA	Design for Manufacturing and Assembly	A design methodology that aims on optimizing the manufacturing and assembly aspects of a product.
DOF	Degrees of Freedom	The number of independent parameters that can describe the position or configuration of a system.
FDM	Fused Deposition Modeling	An additive manufacturing process that involves extruding melted material layer by layer to create three-dimensional objects.
G-code	Geometric code	A programming language used for controlling automated machine tools.
Micro-mechanism		The most simple form of non-assembly mechanisms, e.g. the six basic joints.

Macro-mechanism		The combination of two or more micro-mechanisms.
NA	Non-Assembly	The manufacturing process where parts are designed to fit together without requiring additional assembly steps.
PBF	Powder Bed Fusion	An additive manufacturing process that involves selectively sintering powdered material layer by layer to create three-dimensional objects.
PBF-LB	Powder Bed Fusion - Laser Beam	Powder bed fusion where a laser beam is used to sinter the powder.
STL	Standard Triangle Language	File format used to describe the surface geometry of a 3D model.



Contents

List of Acronyms and Terminology	ix
List of Figures	xv
List of Tables	xvii
1 Introduction	1
1.1 Aim	2
1.2 Specification of issue under investigation	2
1.3 Limitations	3
2 Methodology	5
3 Literature study	7
3.1 Powder bed fusion - laser beam	7
3.1.1 Support structures	7
3.1.2 Surface finish	8
3.1.3 Post-processing	9
3.2 Micro-mechanisms	10
3.2.1 Joints	10
3.2.2 Clearance and powder adhesion	10
3.2.3 Managing support structures	11
3.3 Alternative designs and methods	13
3.3.1 Design for AM	13
3.3.2 Drum and worm design	13
3.3.3 Cage design	15
3.3.4 Self-supporting holes	16
3.3.5 Tilting stops	17
3.3.6 Hemisphere	18
3.3.7 Down-skin	18
3.4 Prismatic joints	20
3.4.1 Build orientation	20
3.4.2 Support	22
3.4.3 Clearance and size	22
3.4.4 Functionality and applications	22
3.5 Revolute joints	23
3.5.1 Build orientation	23

3.5.2	Support	24
3.5.3	Clearance and size	24
3.5.4	Functionality and applications	25
3.6	Cylindrical joints	26
3.6.1	Build orientation	26
3.6.2	Support	27
3.6.3	Clearance and size	27
3.6.4	Functionality and applications	28
3.7	Helical joints	29
3.7.1	Build orientation	29
3.7.2	Support	31
3.7.3	Clearance and size	31
3.7.4	Functionality and applications	31
3.8	Spherical joints	32
3.8.1	Build orientation	32
3.8.2	Support	33
3.8.3	Clearance and size	33
3.8.4	Functionality and applications	34
3.9	Planar joints	35
3.9.1	Applications	35
3.9.2	Substitution	35
4	Results	37
4.1	Manufacturability of micro-mechanisms	37
4.2	Optimizing micro-mechanisms	38
4.3	HTML library	39
4.4	Prototypes	40
5	Discussion	43
5.1	Evaluation of joint toolbox	43
5.2	Difficulties with joints	44
5.3	Validation issues	44
5.4	Macro-mechanisms	44
5.5	Evaluation of sources	45
5.6	Future research	45
	Bibliography	46
A	Appendix	I
A.1	HTML library	I
A.2	Polymer print prototypes	XV

List of Figures

3.1	Split segment to reduce surface contact	11
3.2	Revolute joint with drum shape implemented	14
3.3	Revolute or cylindrical joint with worm shape implemented	14
3.4	Spherical joint with a cage design. The cage can be applied to the the ball or the socket.	15
3.5	Schematic that shows the parameters for a self-supporting hole	17
3.6	Schematic of revolute joints. a) ordinary revolute joint, b) revolute joint with tilted stops implemented	17
3.7	Down-skin areas at two threshold angles of 45° and 75°.	19
3.8	Standard prismatic joint	20
3.9	Profile of prismatic joint manufactured in 90° with the profile being self-supporting	21
3.10	Different build orientations for prismatic joints	21
3.11	Regular revolute joint	23
3.12	Resolute joints in different build orientations	24
3.13	Regular cylindrical joint	26
3.14	Different build orientations for cylindrical joints	27
3.15	Regular helical joint	29
3.16	Thread angle and pitch in helical joint	30
3.17	Helical joints in different build orientations	30
3.18	Regular spherical joint	32
3.19	Spherical joint with the self-supporting hole principle implemented	33
3.20	Spherical joint with an altered opening in the socket	34
3.21	Alternative macro-structure for the planar joint composed of two pris- matic and one revolute joint	35
4.1	Beginning of cylindrical joint page from the toolbox. Full images can be seen in Appendix I	40
4.2	Polymer prototypes of regular joints (green) and redesigns (white), made with Fused Deposition Modeling	41
A.1	Ordinary prismatic joint	XV
A.2	Prismatic joint, cage design	XV
A.3	Prismatic joint, worm design	XV
A.4	Ordinary cylindrical joint	XVI
A.5	Cylindrical joint, self supporting hole	XVI
A.6	Ordinary revolute joint	XVI

A.7	Revolute joint, drum design	XVII
A.8	Revolute joint, worm design	XVII
A.9	Revolute joint, tilted stops	XVII
A.10	Ordinary spherical joint	XVIII
A.11	Spherical joint, cage design	XVIII
A.12	Ordinary helical joint	XVIII
A.13	Spherical joint, hemisphere design	XIX

List of Tables

3.1	How joints can be combined to cover all DOF. R = rotational, T = translational	10
3.2	Peak values for self-supporting holes from 2 mm to 30 mm	16
3.3	Settings for in-skin and down-skin used by Khademzadeh et al. (2022) in his experiments.	19

1

Introduction

Additive manufacturing (AM), commonly known as 3D printing, is a rapidly evolving manufacturing technique and is being used and adapted into many different sectors of manufacturing. This technique makes it possible to create complex geometries in polymer- and metal-based materials. Thus enabling the manufacturing of mechanisms requiring minimal post processing and assembly, called non-assembly (NA) mechanisms, where the entire part is manufactured in one step, eliminating the need for assembly and joining (De Crescenzo & Lucchi, 2017). Hence, using this process in manufacturing saves time, material usage, tools, and processing that would otherwise be required to perform these operations.

This type of manufacturing creates new opportunities that were previously unavailable, since parts can be individualized and more complex designs can be produced. Moreover, NA mechanisms expands the scope of possibilities even further, making even more complicated designs possible. Important possible future use for NA mechanisms is for instance expandable orthopaedic implants in the biomedical industry, where heavy restrictions on weight and volume are present (Leefflang et al., 2021). Another example is the aerospace industry, where lighter weight and reduction of parts is possible by using AM (Pasang et al., 2023).

There are several different AM technologies being used as of 2023. This report only considers the powder bed fusion - laser beam (PBF-LB) process. This technology is constantly being developed, one promising concept being EOS Smart Fusion software, that supposedly removes the need for support structures (Wohlfart, 2022). Because this technology is not accessible yet it was not included directly. However, Khademzadeh et al. (2022) has tested the same principle as EOS without this software. These results have been taken into account in the report.

This project is a bachelor's thesis from Chalmers University of Technology and is carried out over the course of 16 weeks. The report is foremost a prestudy to a larger project about macro-mechanisms in the biomedical industry. However, the results from this report can be used in other fields with the aim to create NA AM mechanisms.

Since the technology is improving every year, it is important to keep the design principles up to date. There is not an established compilation of design guidelines for NA mechanisms in PBF-LB.

The report starts with an explanation about the methodology used in the project

followed by a literature study. The literature study starts with information about the manufacturing technique and how to design for AM (DfAM) followed by information of design principles that are important when manufacturing NA mechanisms. From Section 3.2 the information about the micro-mechanisms starts. First with the general information shared with all joints, followed by chapters that dives deeper in each type and explains how the previous information applies in the specific case.

1.1 Aim

The aim was to create a comprehensive toolbox with design criteria for single-step AM of micro-mechanisms, with a particular focus on NA AM with metals. This toolbox acts as a library from which designs of different micro-mechanisms can be retrieved with the purpose of creating macro-mechanisms.

The resulting library will be part of further studies with the end goal of creating 4D and non-assembly mechanisms for further research and products in various industry's including biotech industry.

1.2 Specification of issue under investigation

From the aim of the project, certain questions arise that need to be further researched and answered. To answer these questions and to achieve the specified goals of the project, the problems were broken down into smaller, more detailed interim goals.

- What types of micro-mechanisms are possible to manufacture using AM technology?
 1. Study the capabilities and limitations of the AM technology.
 2. Research what kind of joints are needed to cover the entire range of motion and function.
 3. Research what kind of micro-mechanisms, have been successfully manufactured using PBF-LB in the past.
 4. Explore if and what redesign is necessary in order to successfully manufacture the micro-mechanism using AM.
 5. Determine what type of micro-mechanisms would actually be possible to manufacture using AM technology.
- How can the micro-mechanisms be optimized for NA AM and how can the optimal result be achieved?
 1. Study the general design guidelines for PBF-LB
 2. Research how micro mechanisms have been designed for NA AM in the past.
 3. List a set of redesign principles and how they can effect and can be applied to different micro mechanisms
- How can the information found during the project be presented in the most effective way?

1. Discuss where the information will be applied and how it should be presented
2. Adjust the data in a way that fits the application

1.3 Limitations

The main focus of the thesis is based on metal PBF-LB process. By limiting the project to this type of manufacturing, the specific challenges associated with this particular method can be researched and explored more in-depth. Thus, all polymer and other metal AM processes will not be included in the final report.

When prototyping, polymer printers will be used for faster and cheaper prototyping but are not included in the literature study. The final library will therefore only consider metal AM. Differences between metals will not be considered.

The project will not focus on a specific product but instead generate general design principles and guidelines that can be applied to further product development. Additionally, the prototype or prototypes that may come as a result of the project will not be tailored for a specific need but instead, be a proof of concept from the theoretical analysis.

The project will only consider existing technology. The modification of machines and tools will not be investigated. To create a higher printability, the geometry and build orientation of the mechanism will be modified.

These limitations are all important to make sure that the project and research are relevant and focused on reaching all the goals previously stated.

2

Methodology

Upon establishing the purpose of the project, a prestudy was conducted to provide an understanding of the subject matter and identify relevant data for the upcoming research steps. Throughout this research, it was important to keep track of what sources were read and imperative to this project. While doing so, different types of joints were identified, categorized, and broken down into six basic types of micro-mechanisms.

With the information about the joints retrieved from the research, in addition to previous knowledge about AM, a preliminary list of important aspects when manufacturing the joints was established. These aspects were brainstormed, discussed, and sorted using the website Mural to provide a good visual representation. Mural was also used to sort the micro-mechanisms and their characteristics. From this, it was determined what kind of data should be presented. Consequently, an appropriate medium to present this data could be chosen. For this project, it was decided to create an HTML file since it allows the user to actively interact with the library.

The next step was to do more in-depth literature studies of all six joints. Information was retrieved from various scientific articles, the AM-company EOS data sheets, and already existing PBF - LB design guidelines. The information retrieved from the studies was then compiled into design guidelines for each joint. On top of this, a few alternative designs were researched for the joints. These redesigns serve as improvements in different aspects of the joints.

Prior to coding the final document, a mock-up of the HTML file was created using the software Figma. This tool was used to document all data collected and conclusions drawn from the literature studies. This made editing the document easier and more efficient while allowing the group to work together in a single file. The Figma file was filled with headers, text, and figures, providing a clear representation of what information to be included in the final document. Another perk of using Figma was that the data and interface could be presented and discussed with experts and supervisors and then edited to improve the product. Additionally, it was all documented in the report, where details were explained in-depth.

To evaluate the functionality of the report's findings, the most essential redesigns were modeled in the CAD software SolidWorks, after the given parameters. It was then prepared in the slicing software PrusaSlicer for polymer fused deposition modeling (FDM) print. The printed models were then tested for strength and functionality to see whether the theory was transferable to reality.

3

Literature study

3.1 Powder bed fusion - laser beam

Powder bed fusion (PBF) is the primary method used for metal AM. In this process a thin layer of metal powder is evenly distributed on a build plate, the powder is then fused at specific locations gathered from the 3D CAD model data. The energy source that fuses the metal powder is either a laser or electron beam, however electron beam will not be considered. When all these specific locations have been fused on the powder bed, a new layer of powder is evenly spread with a blade, called a recoater blade. This process repeats itself until the part is finished. All loose, unfused, powder will remain in its place and act as temporary support during building, but will be removed when the entire part is finished (King et al., 2015).

To produce the CAD model, it must first be prepared with a model slicer software. The software converts the CAD model data, typically in STL (Standard Triangle Language) format, to G-code, a programming language that tells the hardware the correct way to produce the model layer-by-layer. G-code supplies the machine with information about where to deposit the energy from the laser, using coordinates in a 3D space. The slicer software is also used to generate support structures based on user-defined attributes (Vaidya & Anand, 2016).

3.1.1 Support structures

Support structures refer to the sintered structure or the excess powder that is used to support the model during the manufacturing process. Both of which is removed when the object is finished. The main uses of supports are to transfer heat, reduce residual stresses, and reduce the effect of recoater forces (Wohlfart, 2019). The design of the support structures is crucial since it influences the quality of the part, material consumption, and post-processing time (Wang et al., 2021).

The thermal conductivity of metal powder is far less than that of solid structures. Without the proper disposal of heat the part risks thermal defects such as warpage and shrinkage of model (Wohlfart, 2019). Warpage refers to the deformation of the part caused by uneven cooling, which can affect the mechanical properties of the part.

Residual stress is a common issue in metal PBF due to temperature differences between layers and locally concentrated energy input (Mercelis & Kruth, 2006;

Wohlfart, 2019). These types of stresses can lead to deformation or even cracks in the object which is why it is important to try and avoid them. Compensating for residual stress is easier than addressing its cause, and can be achieved through pre-deformation or, among other things, designs that are less prone to deformation (Gruber et al., 2022).

During the recoating, of the build plate, forces are acting on the part while spreading the powder. Therefore it is important to securely connect the part to the baseplate via sintered supports (Wohlfart, 2019).

Sintered support is referring to the support structure that is part of the G-code and modeled by the laser as part of the final structure (Vaidya & Anand, 2016). Sintered supports are able to bear more weight compared to other types of support, but is often harder to remove. Therefore the use of these supports within kinetic micro-structures can present difficulties in maintaining the functionality, such as poor surface finish, leading to increased friction within the joint (Cuellar et al., 2018b; Wadea et al., 2022).

Powder support is the support that the coated powder itself gives to the structure and superstructure of the part. The powder fills up cavities of the model and must be removed when the process is finished, which is usually done with compressed air and a brush. Considering this, the extraction of powder support must be carefully designed into each model, allowing adequate space for complete extraction of the powder (Calì et al., 2012; Gibson et al., 2015).

3.1.2 Surface finish

The surface finish of parts produced with powder bed fusion - laser beam (PBF-LB) generally has much rougher surfaces, which affect the fatigue performance and tensile properties of the parts negatively. In order to meet certain qualities these parts might be in need of machining post-production (Cao et al., 2021). Due to certain parts being limited by surface finish, there is great interest in improving this parameter. The surface roughness of PBF-LB processed parts is caused by three possible factors: powder adhered roughness, stair-step roughness, and top-surface roughness (Carter et al., 2022).

Powder adhered roughness occurs when powder particles adhere to surfaces where loose powder comes in contact with molten or hot material. This phenomenon is called powder adhesion and it ensues either when particles are in contact with the solid material or when particles are in contact with molten pools. For vertical or angled builds, powder adhesion is the primary cause for rougher surfaces (Carter et al., 2022). Reducing powder adhesion is therefore of great interest if surface finish is essential for the final product.

Stair-step roughness is intrinsically caused by manufacturing layer by layer and is dependent on layer thickness and build angle. Layer-by-layer manufacturing of parts with inclinations thereby results in surface irregularities resembling a staircase

(Mhlanga et al., 2022). Roughness on non-horizontal surfaces is not only caused by stair-step roughness but also powdered adhered roughness. Although at lower angles the stair-step effect dominates, with increasing angles, powder adhered roughness has a larger impact (Carter et al., 2022).

Top-surface roughness refers to roughness on surfaces that are parallel to the build plane. This roughness is caused by overlapping curvature of individual melt pools and this roughness increases with increasing laser speeds, i.e. decreased overall energy input (Carter et al., 2022). Hence, if high top-surface roughness poses a problem, it can be reduced with lower laser speed.

3.1.3 Post-processing

Depending on the application of parts produced with PBF-LB, post-processing of parts might be necessary. There are several different post-processing techniques, e.g. heat treatment and shot peening, and they are used for different purposes and can substantially differ in cost and efficiency. For instance, parts with bad surface quality may need surface treatment in order to function properly (Subramaniyan et al., 2021).

If support structures have been used in the production of the part, these structures have to be manually removed with tools, e.g. chisel, saw, or grinders. This will leave a rough surface where the support was attached that may have to be subjected to surface treatment (Makerverse, n.d.). Furthermore, post-processing can to a certain degree be used to regulate the mechanical properties of parts. Improved fatigue behavior can be attained with heat treatment by regaining a certain level of ductility and releasing tensile residual stresses (Fernandes et al., 2022).

3.2 Micro-mechanisms

Joints are an important part of a mechanical mechanism and are responsible for both limiting and allowing movement. The greater amount of moving parts within a mechanism, the greater amount of energy will be lost to friction. The friction comes from the adjacent surfaces within the joints and a huge part of making a functional system is to keep this friction to a minimum.

3.2.1 Joints

There are six basic forms of joint types: Prismatic, revolute, cylindrical, helical, spherical, and planar joints (Xiong et al., n.d.). These all have unique properties and are the foundation of every mechanical joint. All other joints can be broken down into these six. For example, the universal joint is built by using two revolute joints. The same reasoning goes for slot and distance joints (COMSOL, 2018). Table 3.1 displays how the six joints combined can cover all the possible degrees of freedom (DOF) that exists.

R \ T	0	1	2	3
0	Rigid	Prismatic	E.g. 2 Prismatic	E.g. 3 Prismatic
1	Revolute	Cylindrical and Helical*	Planar	E.g. 2 Prismatic + Cylindrical
2	E.g. 2 Revolute	E.g. Revolute + Cylindrical	E.g. Revolute + Planar	Free
3	Spherical	E.g. Spherical + Prismatic	E.g. Spherical + Planar	Free

*Helical joint has a linear relationship between the rotational and the linear movement.

Table 3.1: How joints can be combined to cover all DOF. R = rotational, T = translational

3.2.2 Clearance and powder adhesion

Despite the joints being different, there are similar rules and guidelines that apply to all joints. For a joint to function there must be a surface gap inside the joint that allows for the movement. Dross formation, a phenomenon that occurs at down-facing unsupported surfaces and causes dimensional inaccuracies and rough surface finish, together with powder adhesion might cause the joint to merge together (Charles et al., 2022; Khademzadeh et al., 2022). Design guidelines by Kranz et al. (2015) show that there must be a minimum gap of 0.2 mm for two parts to not merge together. However, this only applies to vertical surfaces. Thomas (2009) guidelines suggest a larger gap for surfaces that are tilted downwards due to increased surface roughness being obtained.

The way Kranz et al. (2015) explained the 0.2 mm clearance is that the gap will be approximately 0.1 mm smaller than designed. This is because of the surface

roughness and powder adhesion. 45° surfaces have a much rougher surface because of the increased powder adhesion. The surface is approximately three times rougher compared to 0° (Kranz et al., 2015). That suggests that the clearance will scale the same way and be three times smaller than designed for 45° surfaces. Therefore the minimum clearance for a 45° tilted surface is 0.4 mm.

This means that the clearance inside the joint will depend on the build orientation. There are however ways around this, for example, the implementation of down-skin can lead to successful use of tighter clearances. There are also other ways to lower the clearance that is exclusive to one or some joints. It is important to have tight clearances because larger clearances can contribute to inaccurate movement in the joint (Lussenburg et al., 2021).

To lower the risk of powder adhesion, it is recommended to always reduce the contact surface. Kranz et al. (2015) guidelines show that a long connecting segment can be split up to decrease the surface contact. This can be applied on every joint and there are several methods for this. One way is by using a redesign, such as cage or worm. As shown in Figure 3.1, another method is to split up the segments of a joint into smaller pieces, thus adding a ridged construction to hold everything together. The figure displays a cylindrical joint, however the same principle applies for all other joints. As a result, this will also reduce the amount of friction in the joint (Cuellar et al., 2018a).

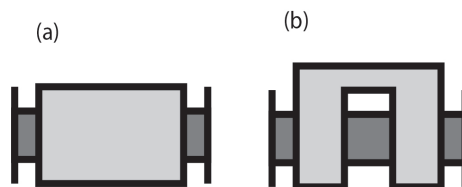


Figure 3.1: Split segment to reduce surface contact

3.2.3 Managing support structures

Because of the nature of the manufacturing technique, there will always be residual powder around and in the joint. This powder needs to be removed, otherwise, the joint may get stuck. There are multiple ways to address this issue, one approach is the cage design (Calì et al., 2012). The way to achieve this can vary depending on the type of joint in question. Another method is to simply increase the clearance but this may result in a looser joint.

Support structures should always be avoided if possible (Thomas, 2009). This is important to improve the surface roughness and avoid unnecessary post-processing. Support structures on the inside of a joint are often very difficult to remove. To be able to remove these supports there should at least be a 5 mm opening (Kumke et al., 2016).

3. Literature study

Apart from these general guidelines for micro-structures, the general PBF-LB design guidelines must also be taken into account. Many of the general guidelines used to derive these micro-structure guidelines are based upon Kranz et al. (2015) and Thomas (2009) papers on PBF-LB rules and guidelines.

3.3 Alternative designs and methods

When manufacturing joints with AM, there are several aspects that have to be taken into consideration, such as support removal and powder extraction. To address these challenges, design modifications could be necessary depending on the specific situation and joint. The following sections describes the most general approaches for altering joint designs. These approaches are applicable to most types of joints. The other, more specific, redesign options for each joint type are discussed in respective chapters.

3.3.1 Design for AM

Design for AM (DfAM) is the process in which the design of a product takes advantage of the different capabilities offered by AM technology. This means redesigning products based on the added benefits that AM brings, as well as the constraints (Diegel et al., 2019). This is accomplished by using guidelines, design principles, processes, and tools which are derived from AM research. Aside from this, organizational and procedural aspects are also taken into consideration in DfAM (Guertler et al., 2022).

DfAM enables the freedoms of AM and in that way reduces the need and importance for, among other things, assembly (Thompson et al., 2016). This means that the traditional Design for Manufacturing and Assembly (DfMA) needs to be reconsidered. DfMA is thus not applicable to the same extent for AM and for that reason it has more or less been replaced by DfAM (Jiang et al., 2022). Therefore understanding and applying DfAM correctly is crucial in order to take full advantage of AM.

One example of DfAM is topology optimization, a mathematical approach using stochastic- or gradient-based algorithms to find the optimal design that meet specified constraints on a geometry. This almost always results in a complex structural layout or design, which means it is usually too difficult for traditional machining to manufacture. However, with layer-by-layer manufacturing such as PBF-LB, it is not nearly as complicated to produce. For example, by using topology optimization, parts can be produced with maximal stiffness with the condition of minimum weight (Guessasma et al., 2019).

3.3.2 Drum and worm design

Drum-shaped design is considered to be one of the most optimal ways to construct a revolute joint with low clearances. Here, the pin is constructed in a drum shape, where the radius decreases from the middle toward each end. Since large joint clearances lead to vibrations and instability this is an important part of making functional AM joints. By constructing the joint with an increased gap towards the openings, it makes for simpler powder extraction and support removal (Cuellar et al., 2018b).

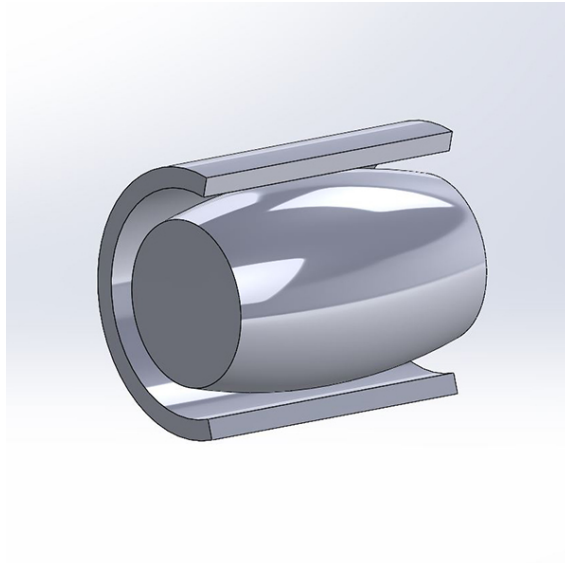


Figure 3.2: Revolute joint with drum shape implemented

Another design principle for revolute joints or other joints with adjacent surfaces is the use of worm design. Worm design is the use of evenly distributed teeth along the axis of the pin. The worm design is based on several parallel cylindrical segments, with a set dimension of width and a number of teeth (Wei et al., 2016).

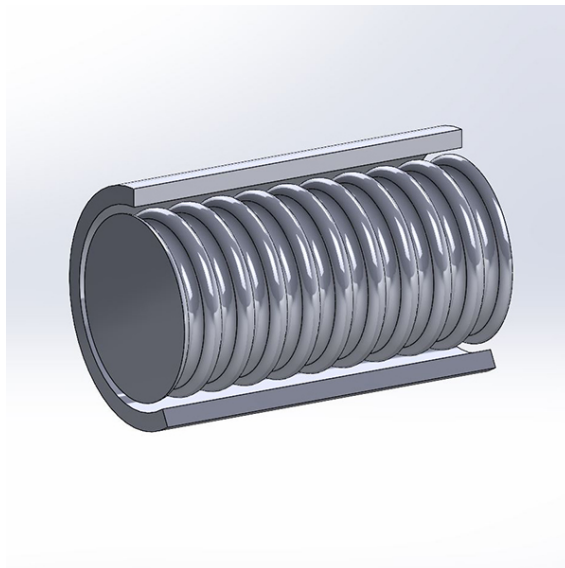


Figure 3.3: Revolute or cylindrical joint with worm shape implemented

The main benefit of using the worm-shape is that sintered supports are no longer required in most build orientations. During testing made by Wei et al. (2016), it was determined that as long as the slope of the teeth is greater than 45° , seen from the axis, the geometry will be self-supporting during manufacturing.

The worm-shaped design outperforms both normal-shaped and drum-shaped designs

due to its relatively low amount of vibration and therefore smoother operation. Because of the effective mitigation of vibration, the worm-shape also performs well with asymmetric loads. This correlation can be applied to most joints; low vibrations, i.e. tighter clearances, leads to an increased dynamic performance (Wei et al., 2016).

3.3.3 Cage design

Cage design implies that the entire or a portion of the joint is designed similarly to a cage or mesh. The main inspiration for this comes from Cali et al. (2012), where different types of cage designs for ball joints were explored. Their conclusion was that all the different designs were functional.

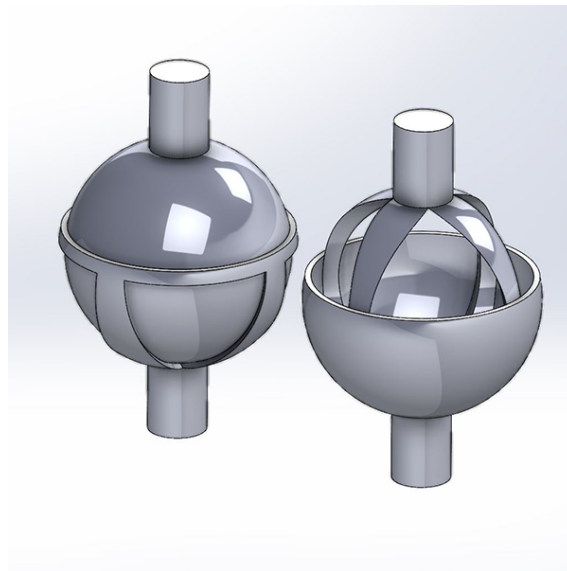


Figure 3.4: Spherical joint with a cage design. The cage can be applied to the the ball or the socket.

The gaps in the cage allow for easier support removal as well as a way for the powder to escape, while the lower surface area leads to lower friction. Additionally, sintered support can be built through the mesh to support structures on the other side. This allows for such support structures to be removed easier and without connecting the supports to the inside of the joint, hence improving its surface finish (Cali et al., 2012).

Another positive aspect of cage design is that it can be applied in almost every type of model, even if it is not a joint. Advantages that apply to all structures are lowered weight and material usage, which means that the manufacturing cost is brought down (Cali et al., 2012).

There are two main aspects to consider before applying a cage design. The first is complexity. It is a lot more complex to design an AM lattice structure than a solid model. The second aspect is stability. A lattice structure will for obvious reasons

not have the same structural integrity as a solid part of the same size. Apart from the structure being overall weaker, depending on the design, the lattice structure will have anisotropic mechanical properties that need to be considered before application (Stanković et al., 2017).

3.3.4 Self-supporting holes

When manufacturing holes with PBF-LB, build orientation is an important aspect. Building vertical holes can be challenging, especially without the use of support structures. Tests made by Thomas (2009) show that larger holes start to distort downwards at the top. Kranz et al. (2015) claim in their design guidelines that holes without support can successfully be built up to 12 mm in diameter. Holes larger than that can be built with support structures, but they can be difficult to remove. Instead, Thomas (2009) presents a redesign solution. By adding a self-supporting peak to the hole, the risk of sagging is greatly reduced. Values are presented for holes with sizes ranging from 2 mm up to 30 mm, as shown in Table 3.2. The values in the table are optimized to maximize the circle circumference and minimize the peak height.

Hole \emptyset	Circle Height	Peak	Peak start	Peak top
2 mm	1.85 mm	0.3 mm	31.69°	28°
4 mm	3.38 mm	0.95 mm	38.52°	28°
6 mm	5.63 mm	0.95 mm	38.52°	28°
8 mm	7.31 mm	1.66 mm	45.05°	28°
10 mm	8.95 mm	2.6 mm	51.98°	28°
12 mm	10.58 mm	3.7 mm	47.32°	28°
14 mm	12.22 mm	4.58 mm	48.94°	28°
16 mm	13.97 mm	5.325 mm	45°	n/a
18 mm	15.76 mm	5.942 mm	45°	n/a
20 mm	17.36 mm	6.769 mm	45°	n/a
22 mm	18.96 mm	7.591 mm	45°	n/a
24 mm	20.63 mm	8.338 mm	45°	n/a
26 mm	22.27 mm	9.114 mm	45°	n/a
28 mm	23.76 mm	10.04 mm	45°	n/a
30 mm	25.4625 mm	10.75 mm	45°	n/a

Table 3.2: Peak values for self-supporting holes from 2 mm to 30 mm

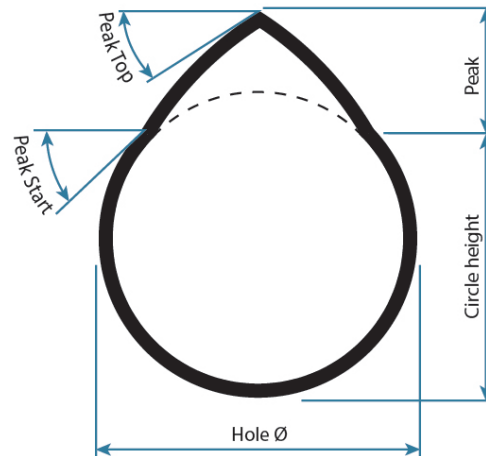


Figure 3.5: Schematic that shows the parameters for a self-supporting hole

3.3.5 Tilting stops

A stop can be required on joints that risk slipping out of their sockets when they are in use. The main joints this applies to are prismatic, cylindrical, and revolute joints. Manufacturing parts similar to a washer at the end of a socket can be complicated because of the support requirements both inside the joint and next to the washer.

The tilting stops redesign is a way to manufacture the stops at an angle so that they can be manufactured without support structures and still be functional. Kranz et al. (2015) paper on design guidelines found the acceptable range of tilting the detail.

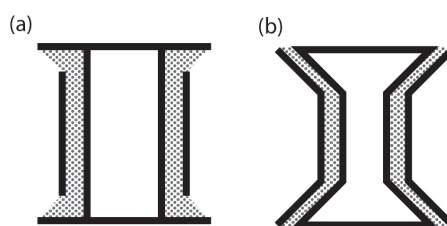


Figure 3.6: Schematic of revolute joints. a) ordinary revolute joint, b) revolute joint with tilted stops implemented

As shown in Figure 3.6, the stops in the revolute joint should be tilted like a cone to still allow rotation and prevent translation. The angle can vary but the maximum angle is 45° or there will be a need for support. One important aspect is that the stop is self-supporting everywhere on the model. The clearance between the stop and socket should be 0.4 mm because of the angled surface as explained in Section 3.2.

3.3.6 Hemisphere

Hemisphere is a redesign option for NA AM mechanisms, which can be applied to optimize the functionality of joints. In order to avoid mechanisms getting wedged between sections as a result of tight tolerances in conjunction with uncleaned powder increasing friction, changes to several joints can be constructed.

A method for solving these types of friction related problems is dividing the main components of a joint into several unconnected parts, all while the function and motion of the joint remain unaffected, as shown by Kranz et al. (2015) guidelines. For example, instead of a prismatic joint being constructed with the help of a continuous rail in which a component slides along, the rail can be divided into several blocks, with gaps between them to allow for powder removal while not compromising on function. However, problems such as fitting errors could arise from this method, resulting in collisions from alignment. To account for this, the shape of the blocks can be constructed to allow for the smooth operation of joints. A functional solution is with a hemispherical design, as this means that if a part of the joint is slightly off axis, it will not get stuck against a square edge. The radius of the hemisphere will push the part perpendicular to the joint's movement until it is on axis.

In helical joints, instead of creating continuous threads along the axle, a series of hemispheres can be placed around it in a helical pattern, allowing for powder to be easily removed in the spaces between these hemispheres, along the thread-grooves (EMS, 2016). Although there are no established standards in the construction of these threads, specific standards like pitch angle can still be used to create appropriate designs.

The cage design can be extrapolated from this method, where the solid parts of the cage retain the overall structure while allowing for powder to be removed between them.

3.3.7 Down-skin

The body of the manufactured model can be broken down into two parts: the down-skin and the in-skin, i.e. the regular build. "The term 'Down-skin' is used for such downward overhanging surfaces of a part that is not supported during building neither by previously solidified layers nor the building platform at the bottom. Instead, the melt pool in the down-skin area is supported by unfused powder particles" (Khademzadeh et al., 2022, p. 2).

The AM company EOS released a technology that made manufacturing without support easier. They call it Smart Fusion (Wohlfart, 2022). The essence of Smart Fusion is that it lowers the laser power when there is a risk for powder adhesion. Khademzadeh et al. (2022) used the same principle to lower the power on the down-skin to get lower dross formation. The experiments demonstrated that a ball joint with a clearance of 0.2 mm and down-skin applied on a 75° threshold angle gave a successful joint.

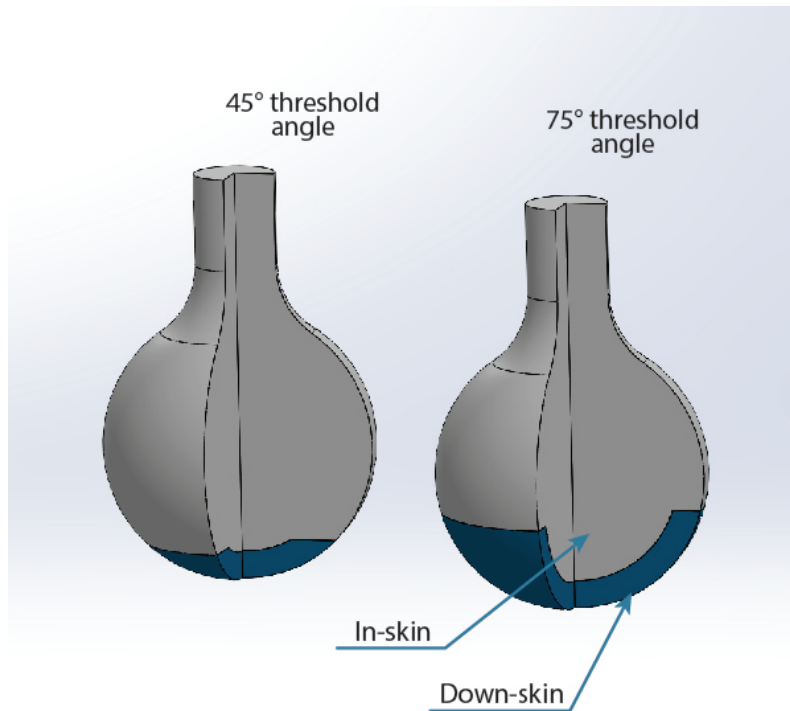


Figure 3.7: Down-skin areas at two threshold angles of 45° and 75° .

In-skin		
Parameters	Hatching	Border
Laser power [W]	155	75
Scanning speed [mm/sec]	1200	1000
Chess size [mm]	4.18	-
Input energy density [J/mm^2]	58	34
Down-skin		
Laser power [W]	113	55
Scanning speed [mm/sec]	1200	1000
Chess size [mm]	2	-
Input energy density [J/mm^2]	42	25

Table 3.3: Settings for in-skin and down-skin used by Khademzadeh et al. (2022) in his experiments.

This down-skin principle can be applied to all joint types. It can lower the required clearance to 0.2 mm everywhere because of the decreased dross formation. EOS claims that the Smart Fusion can manufacture down to 13° without support compared to the previous 45° standard (Wohlfart, 2022). Consequently, it is not recommended to use the down-skin principle to manufacture large flat horizontal down-skin areas without support.

3.4 Prismatic joints

The prismatic joint or sliding joint has one DOF, it moves linearly along its axis, consisting of two parts, the slot, and the beam, that slide against each other. This joint can not rotate in any direction and it is therefore common for the cross section to be polygonal to deny unwanted movements. The prismatic joint usually contains some kind of stop to prevent the beam to escape and be dismantled from the slot (COMSOL, 2018).

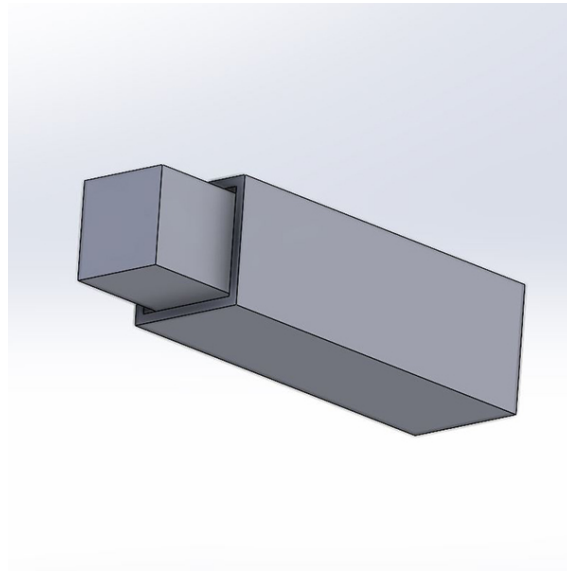


Figure 3.8: Standard prismatic joint

3.4.1 Build orientation

Since the prismatic joint consists of a slot and beam, build orientation is important to consider when manufacturing to avoid the use of support materials. Manufacturing the joint with the DOF vertically is the least complicated way to avoid sintered support structures inside the joint. This also results in a smooth surface finish with lower friction on the inside (Cuellar et al., 2018b).

When manufacturing the joint in an upright position, it can be tilted up to 45° without requiring the need for support. The clearance must be increased unless down-skin is used, otherwise, it will impair the joint's functionality (Khademzadeh et al., 2022). An important note is that a tilted position should have increased clearance on the tilted sides to prevent jamming (Kumke et al., 2016). Note that tilting the joint 45° does not imply that all sides are tilted, certain sides can still be straight and therefore have lower clearances.

If the joint is manufactured horizontally, the shape of the prism can be altered to minimize support structures. The maximum angle at which a self-supporting wall can be manufactured with PBF-LB without supports is 45° (Khademzadeh et al., 2022). Therefore it is possible to manufacture a joint where the sides of the prism

are self-supporting, allowing for the joint to be manufactured in a horizontal, or near horizontal position.

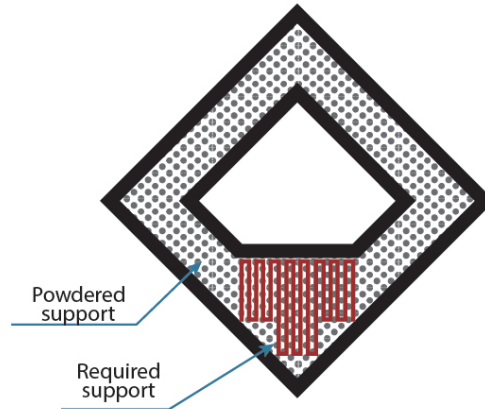


Figure 3.9: Profile of prismatic joint manufactured in 90° with the profile being self-supporting

It is important that the hole in the slot's cross section is self-supporting to avoid support inside the joint. There is no need for supports on the sides for a cross section such as the one in Figure 3.9. The only place where support is required while manufacturing horizontally is at the bottom. To be able to remove this support material, a minimum of 5 mm gap is required (Kumke et al., 2016). To achieve this, an enlarged gap at the bottom is required. Redesign options such as cage design, and worm design can as an alternative be implemented to lower the support requirement.

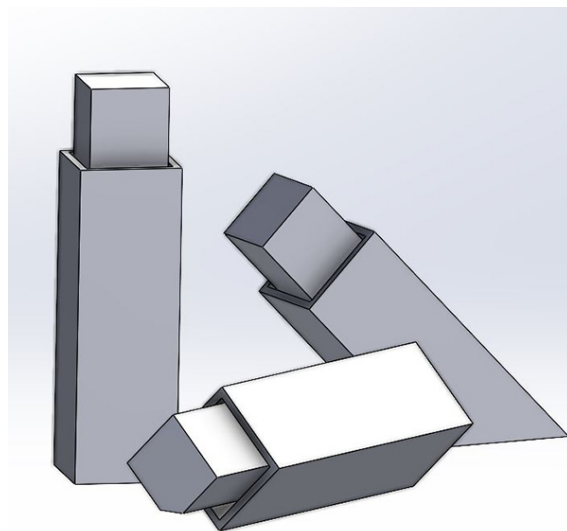


Figure 3.10: Different build orientations for prismatic joints

3.4.2 Support

When the joint is manufactured horizontally the cross section must be self-supporting to avoid support structures inside the joint. The profile is self-supporting if no angle is less than 45° (Khademzadeh et al., 2022). Additionally, powder will appear inside the joint and to assist powder removal, a cage or worm design is recommended, more details in Section 3.3

3.4.3 Clearance and size

Because the joint's clearance depends on the surface angle, there will be different clearance on different parts of the joint. In vertical build orientation, a 0.2 mm gap will suffice on all sides. If it is tilted 45° , two of the surfaces are tilted while two are still vertical. The 45° surface needs an increase to 0.4 mm. The clearance for horizontal joints will depend on the cross section, but generally, 0.4 mm is recommended. Down-skin can be used to reduce clearance in some cases.

The prismatic joint can be scaled relatively freely, with regard to clearance and support. Limiting the downsizing is the thickness of the walls and internal rod. Minimum wall thickness is 0.4 mm. The minimum diameter for a self-standing pillar is 0.5 mm but the core needs to be at least 2 mm wide to still retain a square shape (Kranz et al., 2015). Assuming the smallest rectangular prismatic joint manufactured upright. The total side length will be 3.2 mm. Smaller prismatic joints will be hard to create using PBF-LB. If the joint is manufactured horizontally, it needs to be larger, this is because of the required support removal gap. This will substantially limit the size of the joint to a minimum side length of approximately 6 mm.

The only thing to consider when scaling up is that the length is limited for smaller joints if they are manufactured at 45° . This is because of warping in thin and angled walls caused by residue thermal stresses. If the wall thickness is 0.4 mm the length can not exceed 50 mm. (Kranz et al., 2015).

3.4.4 Functionality and applications

Prismatic joints can be combined with many other joints to give them an extra DOF. For example, they can be combined with a ball joint to create a slot joint, which is a joint with four DOF. Alternatively, combining prismatic and revolute joints into a reduced slot joint, allowing for three DOF (COMSOL, 2018).

To minimize friction in the joint a smoother surface and minimal support material are desired. This can be achieved by manufacturing the joint vertically (Kumke et al., 2016). There are also other ways to minimize friction such as applying the design principles of worm and/or cage design.

3.5 Revolute joints

The revolute joint, sometimes referred to as hinge joint or pin joint, is a kinematic pair with one DOF. The motion of the revolute joint consists solely of rotation around a fixed axis and is therefore constrained and does not allow for translational motion (Gallardo-Alvarado & Gallardo-Razo, 2022). Revolute joints are one of the most common joints and appear in many mechanical applications (Sanz-Idirin et al., 2021). The joint resembles and operates similarly to a cylindrical joint, but is equipped with end stops on each side to prevent it from moving linearly.

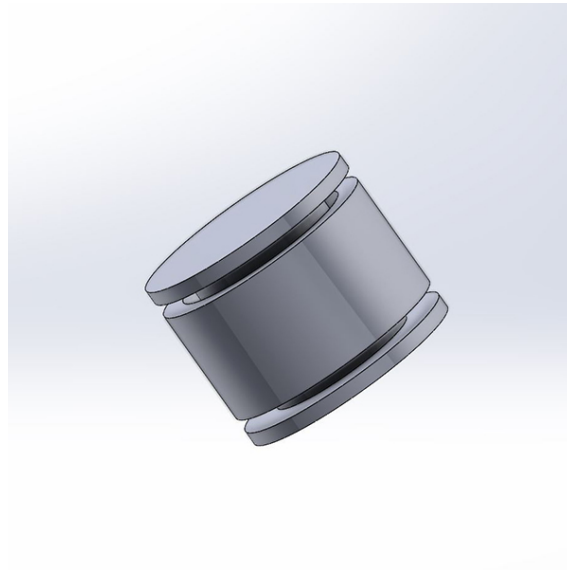


Figure 3.11: Regular revolute joint

3.5.1 Build orientation

Revolute joints should be manufactured along the rotational axis since this prevents the use of support structures between the inner shaft and outer casing. Furthermore, a build direction along the rotational axis results in a better surface finish. This will in turn affect the efficiency of the joint's movement positively (Wei et al., 2016). One aspect to consider is that the constraints are dependent on support structures in this case unless a redesign is made.

Without any redesign, the most optimal orientation to manufacture the joint is at 45° . The core can be built with just an increase in clearance (Thomas, 2009). What makes this the most optimal is that the stops are now angled 45° as well, meaning that they can be built without support (Khademzadeh et al., 2022). However, support structures will be required on the outside of the joint.

It is not recommended, but a drum shape on the inner shaft is beneficial if the joint must be manufactured perpendicular to the rotational axis. The drum shape allows for easy cleaning of residual material because of the wider space in the outer ends, acting as drainage areas for powder supports, while exhibiting the best mechanical

performance. Since there is a need for a 5 mm opening to be able to remove the support, the size of the joint will be limited in this build direction (Kumke et al., 2016). This is unless a design principle that eliminates the need for support structures is applied, such as the drum shape. The support could be avoided if the machine is able to bridge the gap or, down-skin, and drum shape is used. Additionally, building in this direction means that holes can not be larger than 12 mm without creating too much dross (Kranz et al., 2015). This limits the size of the joint but can be overcome with the self-supporting hole redesign.



Figure 3.12: Resolute joints in different build orientations

3.5.2 Support

Support is crucial to avoid in revolute joints because the stops on each side make it hard to remove, hence both powder and support structures can cause problems. If support structures are required inside the joint, a design principle that allows manufacturing without support is strongly recommended. These include worm, drum, down-skin, or changing build orientation. It can also be beneficial to implement a cage design to assist in removing the unused powder.

Another location where support is commonly required is at the stops. The stops can also be modified to minimize and remove the support structures. A drum shape or a cage design can minimize the support required. One method to prevent supports in the stops is with the tilted stop design which is illustrated in Figure 3.3.5.

3.5.3 Clearance and size

For vertically manufactured joints, the core has only vertical walls which means that the clearance can be 0.2 mm. However, the stops are horizontal which means that they require support structures unless an appropriate redesign has been applied. The clearance between the stops and bearing consequently has to be large enough

for the support to be removed.

When the joint is manufactured horizontally, the stops are now vertical and can have a 0.2 mm clearance. The core on the other hand requires support on the bottom and possibly on the top unless self-supporting holes are applied on the bearing. The circular shape gives a 0.4 mm clearance but a 5 mm opening for support material should be kept (Kumke et al., 2016). The clearance has to be adjusted in order to account for that.

With a minimum wall thickness of 0.4 mm and the minimum core diameter being 0.5 mm (Kranz et al., 2015), it can be deduced that a revolute joint, with a diameter smaller than 1.7 mm will be difficult to manufacture. The length of the joint should be kept short to minimize the risk of powder adhesion. It will also be difficult to produce shorter than 1.7 mm for the same reasons. Manufacturing with the wall thickness of 0.4 mm around the core and tilting 45° will result in a maximum length of the joint of 50 mm (Kranz et al., 2015). When the joint is tilted 45° both the stops and core needs 0.4 mm clearance.

3.5.4 Functionality and applications

Two revolute joints can be combined to create a universal joint with two DOF (COMSOL, 2018), which can be used to transform rotational forces along two axes that does not line up.

The revolute joint has two kinds of surfaces that account for the joints friction. These are the surfaces inside the joint and on the sides between the stops. Obtaining a smooth finish on both these surfaces can be challenging as they are never manufactured in the same direction. Friction can be decreased with cage, drum and worm design.

3.6 Cylindrical joints

Cylindrical joints allow for linear and rotational movements between two parts, providing two DOF, linearly along the same axis that it rotates around. The cylindrical joint is similar to the prismatic joint but has a circular cross section which allows for the rotation. In many cases they include a stop that prevents the core from sliding out of the socket (COMSOL, 2018).

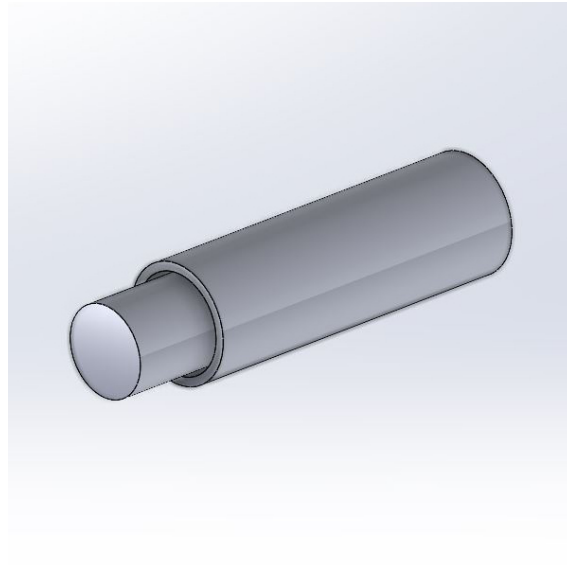


Figure 3.13: Regular cylindrical joint

3.6.1 Build orientation

Manufacturing cylindrical joints vertically, typically produce the most precise and accurate outcome because of the lower surface roughness of the vertical walls (Thomas, 2009). Similarly to prismatic joints, the joint can be tilted 45° with few complications. The only aspect to consider is the necessary increased clearance (Thomas, 2009).

It is possible to manufacture the cylindrical joint horizontally. However, support structures will be required inside the joint and it is therefore not a recommended build orientation. Another thing to consider when manufacturing horizontally is that the maximum hole that can be manufactured in that direction is 12 mm (Kranz et al., 2015). This limits the size of the joint but it can be avoided with the self-supporting holes principle.

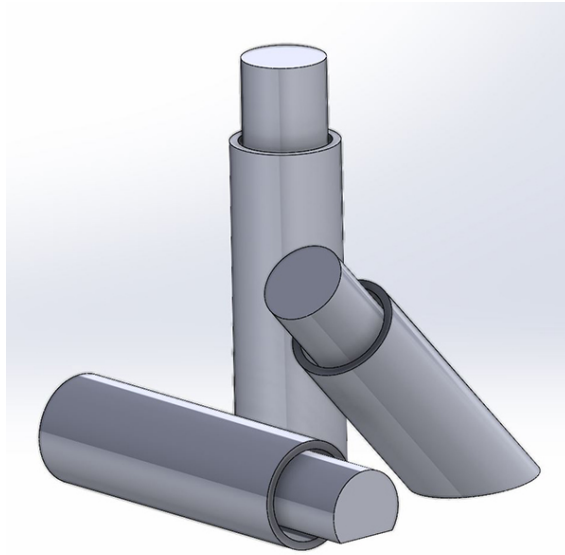


Figure 3.14: Different build orientations for cylindrical joints

3.6.2 Support

Avoiding sintered support could be done by adjusting to a vertical build orientation. If the orientation can not be changed, sintered support will often be needed to create vertical holes larger than 12 mm because of droop formation, unless the self-supporting principle is used (Kranz et al., 2015). Another instance where support can be needed is to support the core inside the joint. If the cylinder is tilted, down-skin or larger clearance could also be used to manufacture the tilted surfaces without sintered supports (Khademzadeh et al., 2022).

Regarding the removal of powder support, the use of a worm-shaped joint design is effective. This creates a larger clearance at the ends of the joint, allowing for easier powder removal (Chen & Lu, 2011). If a drum shaped design would compromise the stability of the joint, a worm design might be applied instead. The cage design is also an option to assist in powder removal.

3.6.3 Clearance and size

When the joint is manufactured vertically, the clearance can be 0.2 mm because the joint only consists of vertical walls. When the joint is tilted 45° the walls are not vertical anymore. Because of the circular profile shape, the walls span from 0° to 45° . To prevent any powder adhesion in the more sloped parts of the cross section without making a varying clearance inside the joint (Thomas, 2009), the clearance should be set to 0.4 mm unless down-skin is used. Manufacturing horizontally means a vertical circular cross section. The clearance should for that reason be 0.4 mm.

In the vertical build orientation, the cylindrical joint does not have many limitations on how it can be scaled. The thinnest possible wall thickness is 0.4 mm and the smallest self-supported pillar is 0.5 mm (Kranz et al., 2015). This means that a

cylindrical joint smaller than 1.7 mm will be difficult to manufacture. Scaling up is no problem when manufacturing vertically. If however the joint is tilted 45° and the wall thickness is 0.4 mm, the longest joint possible to create is 50 mm (Kranz et al., 2015).

When using the horizontal build orientation, there needs to be a 5 mm opening for support structures to be removed (Kumke et al., 2016). That will limit the smallest size possible to create. The smallest joint in this case will be approximately 9.4 mm in diameter. Also, there is a limit on how large the hole in the socket can be. The maximum hole size is 12 mm (Kranz et al., 2015). To overcome this, the self-supporting holes principle can be applied.

3.6.4 Functionality and applications

Similar to the prismatic joint, the cylindrical can be used to give a structure an extra DOF if the rotation does not matter. For example, how it is applied in a slot joint (COMSOL, 2018).

The function of the cylindrical joint is dependent on the balance between friction and clearance. Methods to lower the friction without decreasing the clearance include worm, cage designs, and adjusting the build orientation.

3.7 Helical joints

Helical joints, sometimes referred to as screw joints, screw pairs, or helical pairs, consist of two rigid bodies joined together, allowing for both translational and rotational motion. The shape of the joint restricts the movement of the bodies to a specific helical path, meaning that it is fixed in all angles except one, thereby enabling motion in one DOF. The translation length is coupled with the rotation angle by a linear equation (Ahmadinezhad et al., 2015). One common example of a helical pair is a bolt and a nut.

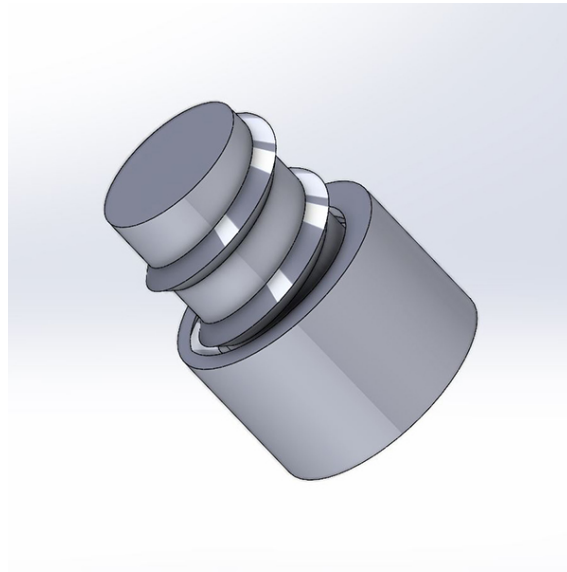


Figure 3.15: Regular helical joint

3.7.1 Build orientation

When producing a screw-shaped object using AM technology, the orientation of the object has a significant impact on the need for support structures and post-processing work. The helical joint is very similar to a cylindrical joint (Ahmadinezhad et al., 2015) and the same orientation principles apply, more details in Section 3.6. The optimal way is therefore to manufacture in the vertical orientation, the only additional thing to consider is the threads. The threads must have an angled profile since a horizontal overhang can only stick out 0.3 mm before it starts to bend upwards (Kranz et al., 2015). Utilizing down-skin is a way to overcome this.

Similar to the cylindrical joint, when manufacturing horizontally, the bottom needs to have a larger opening for support structures to be removed. The self-supporting holes guideline may also need to be applied, as shown in Figure 3.5. This means that there will be parts of the joint that will be missing threads. This is not necessarily a problem. An important aspect is to make sure that there are enough threads interlocking at all times to make the joint work. This will lower the strength of the joint and make the design process harder. Therefore, even if it is possible, it is not recommended to manufacture helical joints horizontally.

3. Literature study

Manufacturing a helical joint at a 45° angle can also work depending on the thread profile. There are two things dictating whether this is possible, the thread angle and the pitch of the thread. If the thread angle is greater than 90° the threads will still be manufactured at a positive angle and be self-supported. The same goes for the pitch of the thread. With a greater pitch, the threads gain support from themselves along with the support from the core which results in a more favorable condition for a successful result.

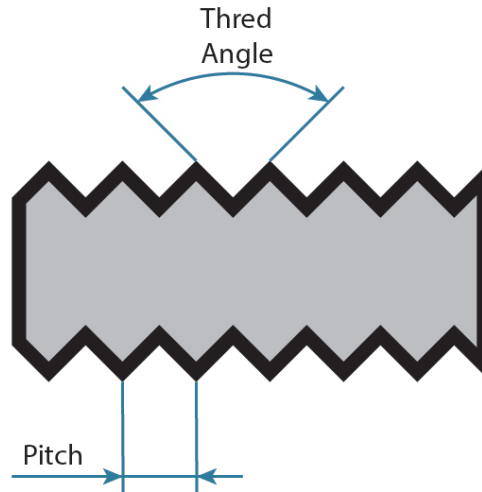


Figure 3.16: Thread angle and pitch in helical joint

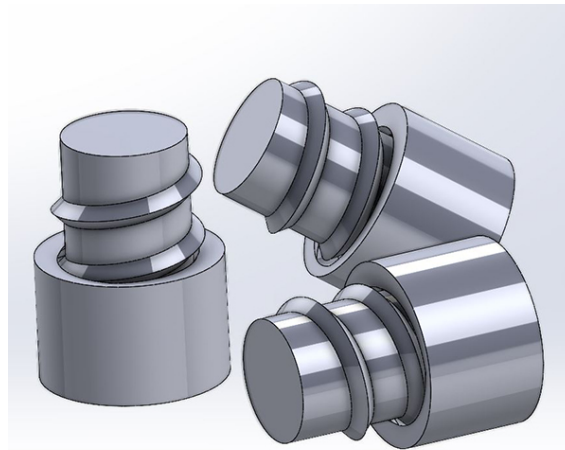


Figure 3.17: Helical joints in different build orientations

3.7.2 Support

The potential need for support is the same as for cylindrical joints, which is discussed in Section 3.6. They can be solved in similar ways: self-supporting holes, down-skin, and changing build orientation.

It is important to get the powder out from inside the joint. The best way to do this in a helical joint is the hemisphere design. The threads should be substituted for an array of hemispheres with gaps in between allowing easier support removal. The cage design is recommended in most other joints for this purpose as well. However, in this case, it can be difficult to implement the cage design alongside the thread and is therefore not recommended firsthand.

3.7.3 Clearance and size

Generally, the core of the screw can have the same clearance as a cylindrical joint, meaning 0.4 mm. However, if manufactured vertically, the clearance would only need to be 0.2 mm. The threads should on the other hand always have 0.4 mm clearance unless down-skin is used. This is based on the shape of its profile.

Assuming all the minimum dimensions: walls, 0.4 mm; clearance, 0.4 mm; threads, 0.3 mm; core, 0.5 mm (Kranz et al., 2015). This sums up to a total joint diameter of 2.7 mm. A smaller joint will be difficult to produce. Even though this is possible, it is not recommended to manufacture at this size. A helical joint of this size would not be able to withstand a lot of linear force. For scaling up, the same principles as cylindrical joints apply as well, more details are in Section 3.6.

3.7.4 Functionality and applications

The helical joint is excellent at easily adjusting distances. The pitch can be adjusted to change the linear to rotational motion ratio. It can however be difficult to create a thread that fits with a standard bolt. Threads that should be used for this should have a tap run over them before usage, to maintain the same precision as a standard bolt (Thomas, 2009). The threads increase the surface contact and therefore increase the risk of powder adhesion and the joint getting stuck (Kranz et al., 2015).

3.8 Spherical joints

The spherical joint or ball joint has three DOF and is thereby free to rotate around all axes. The joint consists of a ball and a socket. The socket's function is to hold the ball in place while still allowing the ball to rotate freely inside the socket (COMSOL, 2018).

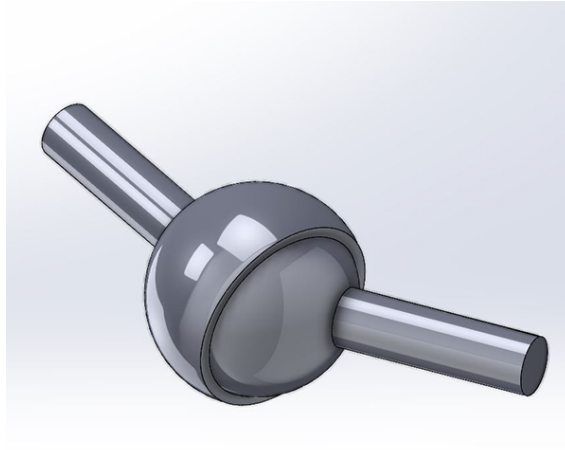


Figure 3.18: Regular spherical joint

3.8.1 Build orientation

Adjusting the build orientation can decrease the need for sintered support or down-skin on the inside of the joint. By applying the general design principles of AM, orientations can be found where the inside of the joint is always built within angles for self-support. The weak spot in this method is the top of the socket. The machine must be able to bridge over the ball, filling the gap. PBF-LB machines can only build vertical holes up to 12 mm in diameter (Kranz et al., 2015), greatly limiting the size of the joint. One way around this is to apply the principle of self-supporting holes to the socket. One thing to note in this orientation is that the socket requires support structures on the outside that needs to be removed. Depending on the size of the joint, down-skin can be used instead.

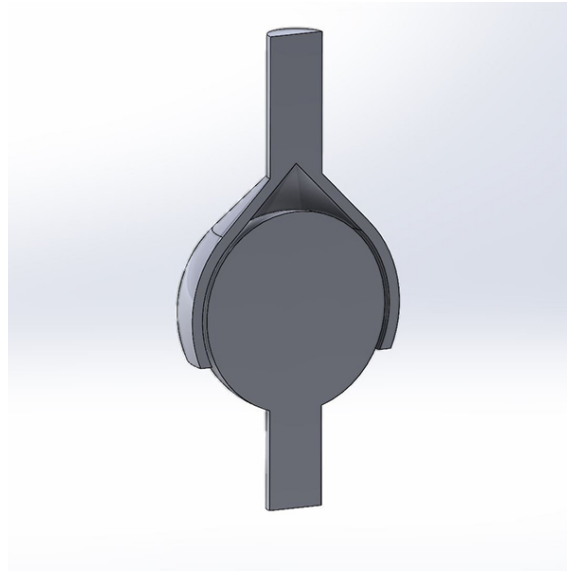


Figure 3.19: Spherical joint with the self-supporting hole principle implemented

3.8.2 Support

Because of the closed nature of spherical joints, support structures are not desirable inside the joint because they would be very difficult to remove (Cali et al., 2012). The main problem with this is clearance. The risk of powder adhesion and the joint fusing is higher if the joint is manufactured as normal without support. One way to solve this is to increase the joint clearance or use the down-skin principle.

A cage design can help with extracting the powder from inside the joint. Other methods that also are beneficial include ball ridge design and self-supporting holes.

3.8.3 Clearance and size

The minimum clearance for an upright gap is 0.2 mm (Kranz et al., 2015). However, because of the spherical shape and enclosed socket, down-skin will be necessary inside the joint if 0.2 mm clearance is applied. Thomas (2009) recommends larger gaps for surfaces with an angle less than 45° . Hence, increasing the clearance to 0.4 mm will make the joint work without the down-skin. The angle of the down-skin can vary, tests made by Khademzadeh et al. (2022) on the spherical joint suggests that 45° down-skin is enough to make the joint work but 75° down-skin will give a more friction-less joint.

There are several factors that can limit the ball joint's size. This is dependent on the build orientation and some of them can be avoided using certain design principles.

1. The wall of the slot can not be less than 0.4 mm. The axis that connects to the ball can not have a diameter of less than 0.5 mm (Kranz et al., 2015). The ball has to be thicker than the axis and some clearance is needed inside the joint. Summing these distances, creating a spherical joint with an outside

diameter smaller than 2 mm will be a challenge. A joint of that size will be very weak and it is not recommended to reduce it down to that scale.

2. Manufacturing concave fillets can be a challenge. For a smooth concave fillet without support, the maximum radius of a hole is 6 mm without any design modifications (Kranz et al., 2015). This rule applies if the socket needs to be filled in the top. This will limit the size of the spherical joint. There are however many ways around this size limitation, using the implementation of design principles such as self-supporting holes, down-skin, or changing the build orientation.

3.8.4 Functionality and applications

Combining two ball joints with a rod will result in a distance joint. This will keep the two ends exactly the same distance from each other no matter the orientation. Ball joints can also be combined with a prismatic joint to create a slot joint. This adds one additional translational DOF (COMSOL, 2018).

The angle of operation is limited by the opening in the socket for the axle. An excessively wide opening in the socket can result in the ball releasing from the socket. Decreasing the opening will result in a stronger joint, but it will not be able to move as much. Changing the shape of the opening can result in a variation in the angle of operation depending on the direction. Doing this gives the opportunity to have a larger angle of operation in a certain direction than otherwise would be impossible (Mavroidis et al., 2000).

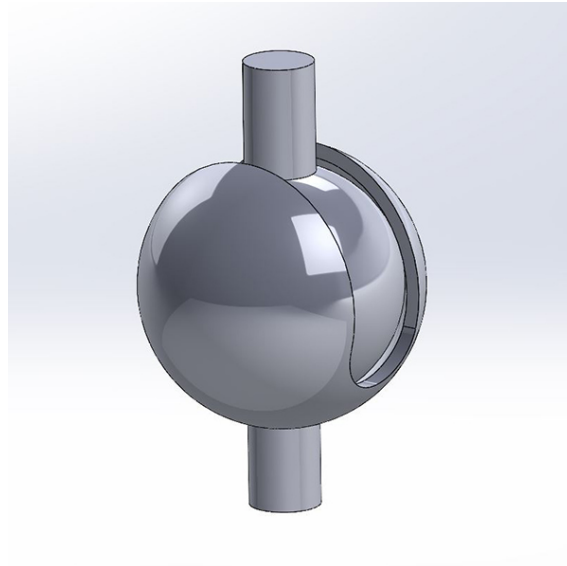


Figure 3.20: Spherical joint with an altered opening in the socket

3.9 Planar joints

Planar joints have three DOF, one rotational and two translational. It involves two planes that slide against each other, resulting in linear motion. In addition to the gliding, these planes can rotate about the axis normal to the plane (COMSOL, 2018).

3.9.1 Applications

Planar joints can be found in the hands and feet of the human body. Although, in mechanical structures, they are very rare due to challenges in optimizing their functionality for those applications. Unlike in the human body, where the joints are held together by various tissues, such as ligaments and membranes, a basic planar joint lacks this type of stability (MacConaill, 2022). Kim et al. (2017) designed an ellipsoid joint and added flexible artificial tendon paths to hold it together. However, when working with NA AM, incorporating these types of flexible tendon paths is not a possibility. The only option is a mechanical solution, however, this is difficult and would result in a very complex mechanism.

3.9.2 Substitution

The inefficiency of planar joints in NA AM does not mean that joints with these sets of DOF are impossible to manufacture. However, it is possible to replicate the functions of a planar joint in a way that is more suitable for AM. For example, combining two prismatic joints and one revolute joint will result in a macro-mechanism that has the same DOF as a planar joint which is illustrated in Figure 3.21).

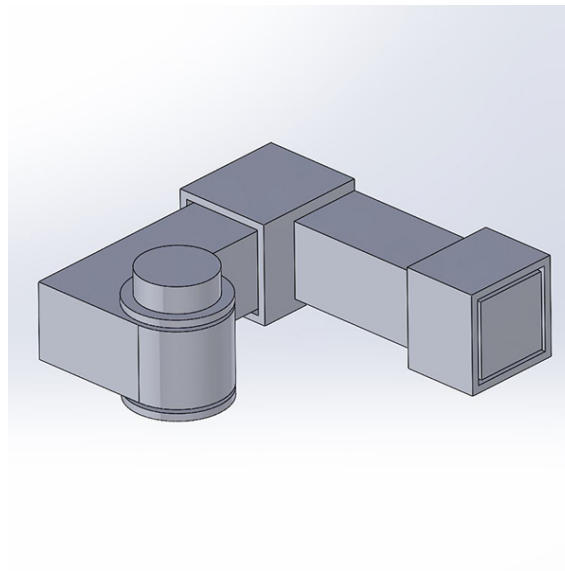


Figure 3.21: Alternative macro-structure for the planar joint composed of two prismatic and one revolute joint

4

Results

In this chapter, the findings from the literature study are presented. This includes what types of micro-mechanisms are possible to manufacture with AM, how micro-mechanisms can be optimized for NA AM, and how this information can be presented in the most effective way. Lastly, prototypes for a few micro-mechanisms, both regular and redesigned, are presented.

4.1 Manufacturability of micro-mechanisms

It was found that micro-mechanisms are composed of six basic forms of joints, namely: prismatic, revolute, cylindrical, helical, spherical, and planar joints. Different combinations of these joints can cover all possible DOF. All other macro-mechanisms, for example, the universal joint and the slot joint, are thereby composed of these six joints. Although the joints differ greatly in design, there are guidelines and rules that can be applied to all joints.

For a micro-mechanism to function there must be a clearance that allows for the movement. The amount of clearance necessary depends on the build orientation, for example, for vertical surfaces there must be a gap of minimum 0.2 mm, or else there is a risk of the two surfaces merging together. However, it is desired to have tight clearances to avoid inaccurate movements in the joints.

The manufacturability of the six different joints varies depending on the design, some of the joints were proven to be easier to produce than others. The prismatic, revolute, and cylindrical joints are to some extent similar in design and can be manufactured with relative ease. Whilst helical, spherical, and planar joints are all a bit more complicated and may require additional planning before the manufacturing process.

The helical joint allows for both translational and rotational motion, similar to the cylindrical joint. However, the design of the helical joint only enables one rotational DOF, the translation length is thereby coupled with the rotation angle by a linear equation. This is usually achieved with threads on one of the parts, and although this feature complicates the manufacturability, it is still possible. It was found that the best orientation for the helical joint was to build it vertically along its axis. The threads need to have an angled profile and a horizontal overhang of a maximum of 0.3 mm.

The spherical joint differs widely from the other joints in both appearance and function. The main complication with the joint is manufacturing the top of the socket. Since PBF-LB can not build vertical holes bigger than 12 mm in diameter, the size of the joint is greatly limited. The minimum clearance between the ball and socket is 0.2 mm, but there is a risk of powder adhesion causing the joint to fuse together.

The planar joint consists of two planes that slide against each other and rotate around the axis normal to the plane, consequently having three DOF. Due to challenges both in design and applications, the planar joint is found in a few mechanical applications. From the information from the literature study, it was therefore concluded that the planar joint is both too difficult and unnecessary to manufacture with NA AM. However, the joint can be replicated by combining two prismatic joints and one revolute joint, which will have the same DOF as a planar joint.

4.2 Optimizing micro-mechanisms

In order to ensure the functionality of joints, certain alternative designs can be applied. For some joints, this might be a necessity, while for others it is a method of improving or adapting the joints to certain situations. For example, altering the design of a part as a means of simplifying and improving support removal or powder extraction.

It was found that by reducing the surface contact in a joint, the risk of powder adhesion and the amount of friction in the joint is reduced. For instance, a drum-shaped design achieves this in a revolute joint by narrowing the pin so that there is an increased gap toward the openings. On top of the reduced friction, this design also assists with support removal and powder extraction.

Worm design is another alternative design for revolute joints or other joints with adjacent surfaces. This design consists of using evenly distributed cylindrical teeth with a slope greater than 45° on the pin. This lowers vibrations and contributes to reducing the need for sintered supports in most build orientations, which results in an overall better dynamic performance.

The cage design revolves around constructing the part as a cage or mesh which leads to lowered weight and reduced material usage. The gaps in the design facilitate the support and powder removal while also reducing the surface contact area and thus the friction. However, this redesign signifies increased complexity in design and reduced structural stability. Therefore, the mechanical properties have to be considered before this redesign is applied.

Manufacturing vertical holes without the use of supports is only possible for up to 12 mm in diameter. For diameters larger than that the risk of the hole sagging increases greatly. One method to improve this is by applying the self-supporting hole design which involves adding a peak to the hole, as shown in Figure 3.5. This greatly reduces the risk of sagging and is an alternative to using support structures within the holes. All in all, this is a redesign option that can be applied to many of

the joints, such as both revolute and spherical joints.

For prismatic, cylindrical, and revolute joints a tilted stop can be applied. This is a method to avoid manufacturing a washer at the end of a socket to stop the joints from slipping out of the socket. The maximum tilt angle of the stop is 45° or else there is a need for support. The clearance between the stop and the socket needs to be 0.4 mm because of the angled surface. In Figure 3.3.5 the comparison between a regular revolute joint and a revolute joint with tilted stops can be viewed.

When manufacturing parts in small dimensions or in unfavorable positions, a hemisphere design can be applied to the part. For example, the rail of a prismatic joint, or the thread of a helical joint can be divided into several hemispherical segments along the intended axis of the rail or thread. This technique both reduces the material usage and the need for supports, as well as avoiding friction related problems as points of contact are much fewer. An added benefit of the hemisphere design is also that by the very nature of the circular segments, if a segment of a joint were to come off the axis, the hemispheres would force the segment on the axis again. Comparing this to a regular segmented design where this could lead to collisions.

Decreasing clearance and building horizontally without supports are two main challenges in designing micro-mechanisms for AM and both of these can be greatly improved with the implementation of the down-skin principle. The technique is based upon unfused powder particles supporting the melt pool of the segments outermost layers. Lowering the lasers power where increased risk of powder adhesion and dross formation is prevalent makes this possible, and allows for clearances as low as 0.2 mm. When using this technique, it is also possible to build at angles as low as 13° without the need for support, compared to the conventional 45° .

4.3 HTML library

The main result of the project is a library of joints in the form of an HTML document. The library includes important data, retrieved from this report, such as clearance, size limitations, and explanations on how they affect the joint. This toolbox is supposed to simplify future work with designing joints for NA AM and address the challenges associated with this process. It is intended for use by engineers, designers, and researchers working in the field of AM. The HTML document also shows the different print orientations for each joint and how they affect manufacturing, as seen in Figure 4.2




Non-assembly mechanism

Cylindrical joints

Revolute joint

Prismatic joint

Helical joint

Spherical joint

Redesign

Cylindrical Joints

Metal AM Design Guidelines



Fig 1: Ordinary cylindrical joint



Fig 2: Cylindrical joints in multiple built orientations

Description

Cylindrical joints have two DOF: Rotational, around its own axis, and translational along the axis. Cylindrical joints usually contain some kind of stop to prevent the bearing from sliding out. Cylindrical joint is in many ways similar to the prismatic joint but with a circular cross section to allow rotation (COMSOL, 2018).

Clearance

To avoid powder adhesion, there must be a gap between the moving surfaces. This required gap is highly dependent on the surface roughness which is affected by the angle of the surface. If the cylinder is tilted, down-skin or larger clearance should be used to print the tilted surfaces (Chen & Lu, 2011).

Application

Cylindrical shares the capability of prismatic joints with the addition of a rotational degree of freedom. It can be combined with structures to give it an extra degree of freedom. For example, combining a cylindrical joint with a spherical joint will give a slot joint. (COMSOL, 2018)

For less powder adhesion and less friction it is good to lower the contact area inside the joint by either dividing the slot into multiple segments or applying a redesign. For example, cage design or worm design. (Kranz et al., 2015)

Support

Support should always be avoided if possible, which is most efficiently done by adjusting the print orientation. (Thomas, 2009)

The most common place where support might be needed is to support vertical holes. This limits the size of which the joint can be printed in 90° degrees, unless the self supporting holes redesign are applied (Kranz et al., 2015). An opening of 5 mm is required to allow support structures to be removed. (Kumke et al., 2016)

There will be powder support in the gaps that needs to be removed for optimal performance. Removing powder support becomes easier by increasing the clearance or by implementing a cage or worm design.

Print Orientation

The print orientation mainly determines whether support is needed or not. Printing in an upright position with the axis orthogonal to the build plate is the best option. It allows for the lowest friction and smoothest joint (Cuellar, Smit, Zadpoor, et al., 2018). The joint can be tilted freely as it can build the tilted walls. Clearances may need to be altered.

Putting the joint horizontal creates problems where support might be needed and is therefore not recommended.

Print orientation	Size	Clearance	Support	Function
0°	Min 1.7 mm diameter	0.2 mm	Not required	Most optimal
45°	Min 2.1 mm diameter. Max 50 mm long.	0.4 mm	Not required	
90°	Min 9.4 mm diameter. Max 12 mm inside diameter	0.4 mm	Not required	Least optimal

Figure 4.1: Beginning of cylindrical joint page from the toolbox. Full images can be seen in Appendix I

The appropriate redesigns are listed for each joint, along with the pros and cons of its application. Clicking on a redesign will result in redirection to a page with a more detailed explanation about all the redesigns.

The toolbox, which takes the form of a static single-page HTML document, can be accessed and utilized in any internet browser. It offers a range of features that allow the user to easily explore its content and navigate around the page. In particular, it includes a menu to the left, which enables users to easily access all the joints and design guidelines included in the library. A back button is also included to allow the user to easily return to the previous page.

The content of the toolbox is derived from the literature study made in this project, the information is restructured and the arguments are slightly reduced. If further reading is required from the toolbox, it refers to the sources used in the literature study as well as this report, allowing the user to dive even deeper into the underlying research behind the guidelines and redesign suggestions.

4.4 Prototypes

Several polymer prototypes were made with FDM printers, mainly to test and demonstrate the functionality of the alternative designs and methods. The redesigns and joints that were manufactured were the following: drum shape revolute joint, worm shape revolute joint, tilted stops revolute joint, cage ball joint, self-supporting holes cylindrical joint, cage design prismatic joint, hemisphere helical joint, worm shape prismatic joint, revolute joint, cylindrical joint, prismatic joint, helical joint, and ball joint.



Figure 4.2: Polymer prototypes of regular joints (green) and redesigns (white), made with Fused Deposition Modeling

All of the polymer joints, including the redesigns, were successfully built and functional. There was no noticeable difference in the performance of the redesigned joints compared to the regular joints. In addition to this, some of the redesigned joints, for example the cage design prismatic joint had lower weight with similar strength and function.

5

Discussion

In the following chapter, the result of the project is discussed. This includes complications, suggestions for improvement in the library, the design of the joints, and how the work was conducted.

5.1 Evaluation of joint toolbox

To present the data obtained from the literature study, an HTML file was constructed with the main goal to present the data in a concise and easy-to-understand manner, eliminating the need for the user to read the entire report. In short, we aimed to make the HTML file as user-friendly as possible. To achieve this the HTML file is slightly simplified and structured in a more comprehensible manner with tables and images displaying the data. All the reasoning is not included in the HTML, which serves as a condensed summary of the key results and a supplement to the report. The report can therefore be seen as a source for further reading.

Interactability is the reason for choosing an HTML file instead of something more common, for example, a PDF. While researching, we discovered that other design guidelines were scattered across hundreds of papers, making it difficult to remember or access the crucial parts. Instead, the HTML file has a clear menu and hyperlinks on every page, allowing the user to go directly to redesigns after reading about a specific joint. It is also possible to go back and forth with the standard browser buttons to navigate the different pages swiftly.

One of the advantageous features of an HTML file is that it has the potential to be updated. HTML is a text-based file, which means that it can be opened in almost any text editor. This makes it easy to add, edit and remove information, improving its adaptability. One consequence of this is that an updated version will not update every copy. However, to prevent mix-ups with different versions, the HTML footer has a version number and a year to display what version is in use.

Regarding user experience and user interface, the main focus has been to present the information in an effective matter, and less on the visuals of the actual pages. However, user based testing of the HTML efficiency has not been done.

5.2 Difficulties with joints

One of the observations made during the literature study was the difficulties of planar joints. It was discovered early in the project that there were not many relevant sources regarding planar joints. Instead, most of them were about biological planar joints. These types of planar joints function because of all the various ligaments that hold them together. For this reason, it was difficult to draw a parallel to a mechanical NA AM planar joint. After discussing both in the group and with our supervisor, we came to the conclusion that it was difficult to manufacture, and did not have an obvious application. In light of this, we chose to exclude the planar joint from the library.

In the literature study, Section 3.9 about planar joints differs from the other sections and explains why it is not suitable for NA AM and how it can be substituted to get the same functionality. In our view, it was important to provide this explanation as a proof of the statement that every mechanical function can be created from Section 3.2.

5.3 Validation issues

AM processes are expensive and time-consuming, making testing difficult, especially when doing several tests with small changes. Due to the scale of the project, testing each variable for every joint in the library was not a viable option. The lack of metal prototyping with PBF-LB, ultimately implies that the findings from the literature studies are as of now purely based on theory and are yet to be validated practically.

This goes for both joint-specific parameters, as well as machine-specific parameters. Most papers used in the literature studies use different PBF-LB machines with individual settings. Since we do not know how certain printers and settings correlate with each other, it is difficult to compare the results.

The prototypes made in plastic functioned as a good proof of concept, functionality-wise. However, these models were lacking many of the aspects associated with PBF-LB, such as powder extraction, heat transfer, warpage, tolerances, and clearances. To take account for the lesser tolerances the models were scaled up to a point where the proportions between the resolution of the printer and the size of the model were similar to that of PBF-LB.

5.4 Macro-mechanisms

The micro-mechanisms evaluated are not stand-alone components but are to be viewed as building blocks for creating more complex structures. Combining the micro-mechanisms into structures called macro-mechanisms, which would be able to perform more elaborate tasks, and more complex movements. With the advent of compliant mechanisms, i.e. mechanisms based on elastic deformation rather than

movement between components, the combination of micro- and compliant mechanisms could create macro-mechanisms with great potential. Though this is enticing, more research is required in this area. Thoughts about how the library should be designed to aid with the construction of macro-structures have been acknowledged. However, that is outside of the scope of this report.

Macro-mechanisms are the reason for the library showing the optimal and second most optimal printing angles for each joint, as macro-structures often require more constraints, and as the placement of each joint is important to its function. Thus, this information is important for the designer to model and place the structure in an optimal way in accordance with the data.

5.5 Evaluation of sources

A crucial part of any literature study is evaluating the relevance and reliability of the sources used. In this case, when studying AM, it is particularly important to try to make sure that they are up-to-date since this is a rapidly evolving technology with new findings all the time. In this report, we have tried to use as much new literature as possible to ensure that we do not miss out on any new important research. However, given that AM is such a fast-evolving technology and research in certain areas is limited, finding recent and at the same time relevant and trustworthy sources has been quite the challenge. Therefore, some sources used are a few years older, but these in combination with the newer sources provide a comprehensive understanding of the field. All in all, the sources in this report have been evaluated to ensure that they all contribute valuable insights.

5.6 Future research

Two important sources for the literature study were Thomas (2009) and Kranz et al. (2015). They both contained design guidelines for AM, but during review it was noticed that they differed. Thomas's research was older and therefore claimed that the clearances needed to be bigger and that the surface roughness was worse. This is not because Thomas was wrong, but rather as a result of the technology evolving between the publication dates of the two papers. Following this pattern, this report may suffer the same fate. This research may be replicated and potentially result in different values and conclusions than those presented here. As of May 2023, EOS is releasing software that claims to eliminate the need for sintered support structures (Wohlfart, 2022). Once released, the new software by EOS may render the findings of this report outdated.

As mentioned in Section 5.3 about validation, no prototyping or testing was made with PBF-LB to confirm the different parameters or principles. This is something that can be further researched. There may be aspects that were overlooked because of this that could be brought up in the future.

Something that was not considered in this report was the material. The limitation

set for the literature study was metal. Different metals have different properties in density, melting temperature, and heat conductivity for example. Manufacturing the same joint with different metal alloys may cause different results, and this could be researched in the future. Another material aspect that was not brought up in detail was the powder quality and what effect it could have had.

This project will act as a prestudy to a promising larger project where the micro-mechanisms would be combined into larger and more complex macro-mechanisms. Further research will therefore be about the function and application of combined joints.

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A

Appendix

A.1 HTML library



Non-assembly mechanism

Cylindrical joints
Revolute joint
Prismatic joint
Helical joint
Spherical joint
Redesign

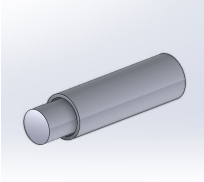
Non-assembly mechanisms

Metal AM Design Guidelines

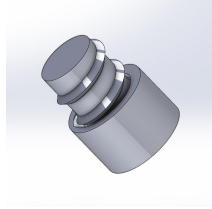


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Cylindrical joint



Helical joint



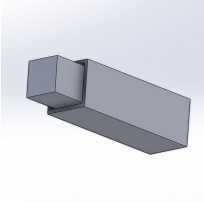
Revolute joint



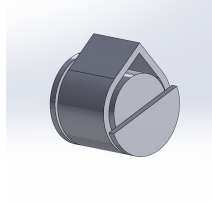
Spherical joint



Prismatic joint



Redesigns



Introduction to library

This library contains data on the six core mechanical joint for AM. The data is for LPBF technology. The source of the information is collected from a bachelors thesis from Chalmers University of technology. The conclusions are based on literature studies and design principles.

How to use

The data is based on a literature studied form 2023. In this literature study it was also observed that the AM capabilities improves every year. The exact parameters in the library will probably change in the future. The usage of the library should be focused on the design principles.

The six core mechanical joints can be found on the home page but also in the menu. Each page about a joint contains some basic values for size limitations, clearance ect, and a short explanation about each parameter. Below the data there are a couple of optional redesign principals that can be used to solve potential problems, improve the joint, and/or brake the basic limitations. More information about the redesigns can be found in by going to the redesign page from the joint pages or in the menu.

The information in these pages are scaled down. If more information is needed, refer to the original report.

List of acronyms

AM - Additive Manufacturing
CAD - Computer Aided design
DOF - Degrees of Freedom
NA - Non Assembly
PBF - Powder Bed Fusion



Non-assembly mechanism

Cylindrical joints

- Revolute joint
- Prismatic joint
- Helical joint
- Spherical joint
- Redesign

Cylindrical Joints

Metal AM Design Guidelines



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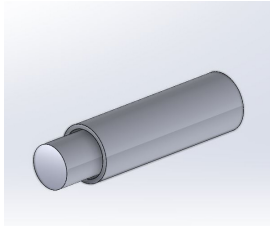


Fig 1: Ordinary cylindrical joint

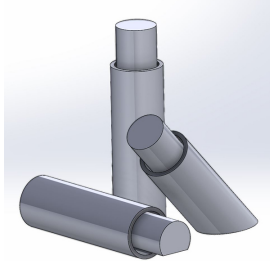


Fig 2: Cylindrical joints in multiple built orientations

Description

Cylindrical joints have two DOF. Rotational, around its own axis, and translational along the axis. Cylindrical joints usually contain some kind of stop to prevent the bearing from sliding out. Cylindrical joint is in many ways similar to the prismatic joint but with a circular cross section to allow rotation (COMSOL, 2018).

Clearance

To avoid powder adhesion, there must be a gap between the moving surfaces. This required gap is highly dependent on the surface roughness which is affected by the angle of the surface. If the cylinder is tilted, down-skin or larger clearance should be used to print the tilted surfaces (Chen & Lu, 2011).

Application

Cylindrical shares the capability of prismatic joints with the addition of a rotational degree of freedom. It can be combined with structures to give it an extra degree of freedom. For example, combining a cylindrical joint with a spherical joint will give a slot joint. (COMSOL, 2018)

For less powder adhesion and less friction it is good to lower the contact area inside the joint by either dividing the slot into multiple segments or applying a redesign. For example, cage design or worm design. (Kranz et al., 2015)

Support

Support should always be avoided if possible, which is most efficiently done by adjusting the print orientation. (Thomas, 2009)

The most common place where support might be needed is to support vertical holes. This limits the size of which the joint can be printed in 90° degrees, unless the self supporting holes redesign are applied (Kranz et al., 2015). An opening of 5 mm is required to allow support structures to be removed. (Kumke et al., 2016)

There will be powder support in the gaps that needs to be removed for optimal performance. Removing powder support becomes easier by increasing the clearance or by implementing a cage or worm design.

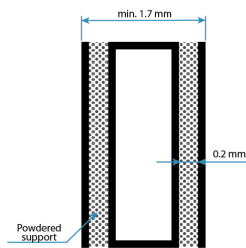
Print Orientation

The print orientation mainly determines whether support is needed or not. Printing in an upright position with the axis orthogonal to the build plate is the best option. It allows for the lowest friction and smoothest joint (Cuellar, Smit, Zadpoor, et al., 2018). The joint can be tilted freely as it can build the tilted walls. Clearances may need to be altered.

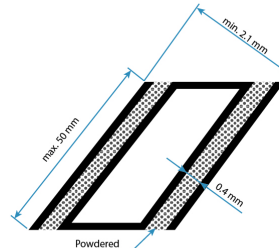
Putting the joint horizontal creates problems where support might be needed and is therefore not recommended.

Print orientation	Size	Clearance	Support	Function
0°	Min 1.7 mm diameter	0.2 mm	Not required	Most optimal
45°	Min 2.1 mm diameter. Max 50 mm long.	0.4 mm	Not required	
90°	Min 9.4 mm diameter. Max 12 mm inside diameter.	0.4 mm	Not required	Least optimal

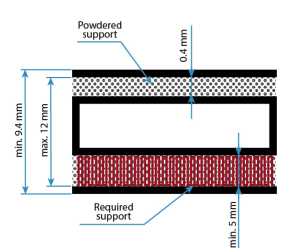
0° Print orientation



45° Print orientation



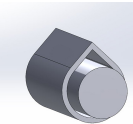
90° Print orientation



Options for redesign

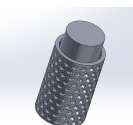
Self Supporting Holes

- Pros:
- Possible to print larger joints at 90° without support
 - Lower friction
- Cons:
- Larger joint



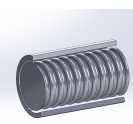
Cage Design

- Pros:
- Easier powder removal
 - Lower friction
 - Less powder adhesion
- Cons:
- More complex design
 - Lower structural integrity



Worm shape

- Pros:
- Easier powder removal
 - Lower friction
 - Less powder adhesion
 - Support free
- Cons:
- Can be difficult in some build orientations



Sources

Sources

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Non-assembly mechanism

Cylindrical joints

[Revolute joint](#)

Prismatic joint

Helical joint

Spherical joint

Redesign

Revolute Joints

Metal AM Design Guidelines



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Fig 1: Ordinary revolute joint



Fig 2: Revolute joints in multiple built orientations

Description

The revolute joint, or sometimes referred to as hinge or pin joint, has one DOF. The motion of the revolute joint consists of rotation around a fixed axis. It is similar to a cylindrical joint but has stops on both sides constraining translation along the axis. (COMSOL, 2018)

Clearance

The clearance between parts in a revolute joint is important for proper function. Too small clearance can cause fusion or powder removal issues, while too large can lead to inaccurate movements. The clearance is dependent on the surface angle (Thomas, 2009). The down-skin principle can be used to reduce clearance.

The revolute joint is similar to the cylindrical joint in many ways. The main difference is that revolute joints have stops on both sides. This means that there are two types of clearances to take into account, the distance between the axle and the bearing as well as the distance between the stops and the bearing. The clearance between the stops and the bearing can usually be built with sintered support since the access for removal is quite good.

Application

Revolute joints are one of the most common joints and have many mechanical applications (Sanz-Ildirin et al. 2021). It is important to note that revolute joints can be designed in several different ways and take on different shapes.

To minimise friction and powder adhesion in the joint, you need to lower the surface contact. Either by splitting out the socket in segments (Kranz et al., 2015), or applying a redesign such as cage, worm or drum design.

Support

Support is crucial to avoid within revolute joints (Thomas, 2009). Both powder and support structures can be difficult to remove due to the stops. Therefore it's highly recommended to use alternative designs such as cage, worm or drum design to ease with removal or help print without support.

One place where support commonly is required is underneath the stops. Although stops can also be modified to minimise and remove the need for support structures. The most noticeable way to prevent supports in the stops are with the tilted stop design. Otherwise, design principles like the drum shape can be used here to create a wider opening at the ends. (Wei et al. 2016)

An important aspect to keep in mind is that if there are support structures built inside the joint, there needs to be at least a 5 mm opening to remove it. (Kumke et al., 2016)

Print Orientation

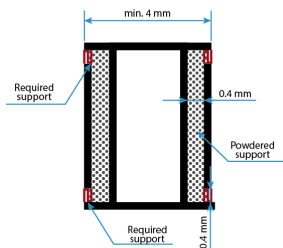
Because of the difficulties of removing superstructures from the joint, the optimal print orientation is 45°. That is the only way to avoid any support structures without using any redesign. To get a tighter clearance around the core. The joint can be built in 0° and the tilted stops principle can be applied.

Similarly to the cylindrical joint, when manufacturing horizontally there will be a need for superstructures on the inside. The difference here is that the revolute joint is not dependent on its length in linear motion. If the joint is short enough that the overhang in the centre can be bridged, it can be built without support. Down-skin will help in this case. Without down-skin this distance is 0.6 mm (Kranz et al., 2015).

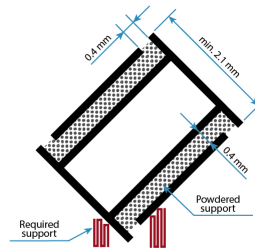
When manufacturing in this orientation, it is important to consider that the maximum hole size is 12 mm (Kranz et al., 2015) and the self supporting holes may need to be applied.

Print orientation	Size	Clearance	Support	Function
0°	Min 1.7 mm diameter	0.2 mm core 0.4+ mm stops	Required	
45°	Min 2.1 mm diameter. Max 50 mm long.	0.4 mm core 0.4 mm stops	Not required	Most optimal
90°	Min 9.4 mm diameter Max 12 mm inside diameter.	0.4 mm core 0.4 mm stops	Required	Least optimal

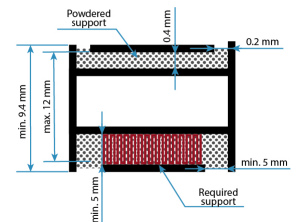
0° Print orientation



45° Print orientation



90° Print orientation



Options for redesign

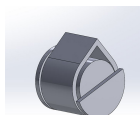
Self Supporting Holes

Pros:

- Possible to print larger joints at 90° without support
- Lower friction

Cons:

- Larger joint



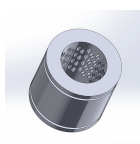
Cage Design

Pros:

- Easier powder removal
- Lower friction
- Less powder adhesion

Cons:

- More complex design
- Lower structural integrity



Tilting stops

Pros:

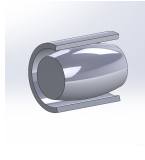


Pros:
Lowers the need for support
Cons:
Larger stops



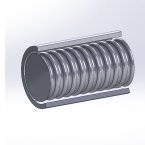
Drum shape

Pros:
Easier powder removal
Lower friction
Less powder adhesion
Cons:
May lead to an unstable joint



Worm shape

Pros:
Easier powder removal
Lower friction
Less powder adhesion
Support free
Cons:
Can be difficult in some print orientations



Sources

- COMSOL. (2018). Modeling mechanical systems in the multibody dynamics module [software documentation]. version 5.5. https://doc.comsol.com/5.5/doc/com.comsol.help.mbd/mbd_ug_modeling.3.07.html
- Thomas, D. (2009). The development of design rules for selective laser melting (version 1). (Doctoral dissertation). Cardiff Metropolitan University. <https://doi.org/https://doi.org/10.25401/cardiffmet.20974597.v1>
- Kranz, J., Herzog, D., & Emmelmann, C. (2015). Design guidelines for laser additive manufacturing of lightweight structures in ti6v4. *Journal of LaserApplications*, 27. <https://doi.org/https://doi.org/10.2351/1.4885235>
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- Sanz-Idirin, A., Arroyave-Tobón, S., Linares, J.-M., & Arrazola, P. J. (2021). Load bearing performance of mechanical joints inspired by elbow of quadrupedal mammals. *Bioinspiration & Biomimetics*, 16. <https://doi.org/https://doi.org/10.1088/1748-3190/abeb57>



Non-assembly mechanism

- Cylindrical joints
- Revolute joint
- Prismatic joint
- Helical joint
- Spherical joint
- Redesign

Prismatic Joints

Metal AM Design Guidelines

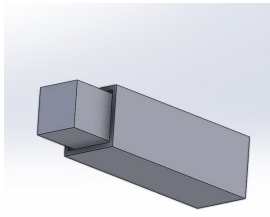


Fig 1: Ordinary prismatic joint

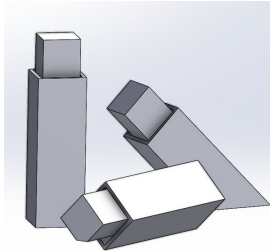


Fig 2: Prismatic joints in multiple built orientations

Description

Prismatic or sliding joints have one DOF. It can move in one linear direction by sliding two parts against each other. It can not rotate and it is therefore common for the cross sectional to be polygonal. A stop is usually included to prevent the internal part from escaping the slot. (COMSOL, 2018)

Clearance

The clearance inside the joint depends on the print angle. Tilted surfaces must have a higher clearance than vertical surfaces. This means, in some orientations, the joint can have different clearances on opposing sides. Down-skin can be used to lower the clearance.

Sizes smaller than the ones in the table are possible to manufacture but they will appear less square and function more like a cylindrical joint. (Kranz et al., 2015)

Application

Prismatic joint is a basic joint. A common application is to combine it with other joints to form a more complex mechanism with one extra DOF. Combining a prismatic joint with ball joints or revolute joints will create a slot joint respectively a reduced slot joint. (COMSOL, 2018)

For less powder adhesion and less friction it is good to lower the contact area inside the joint by either dividing the slot into multiple segments or applying a redesign. For example, cage design or worm design. (Kranz et al., 2015)

Support

Support should always be avoided if possible, which is most efficiently done by adjusting the print orientation. (Thomas, 2009). Down-skin can be used to reduce the support requirements.

The most common place where support might be needed is to support a vertical core when printing horizontally. An opening of 5 mm is required to allow support structures to be removed. (Kumke et al., 2016)

z

There will be powder support in the gaps that needs to be removed for optimal performance. Removing powder support becomes easier by increasing the clearance or by implementing a cage design or worm design.

Print Orientation

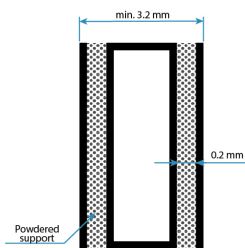
To avoid sintered supports inside the joint and achieve a good surface with low friction, it is best to print the prismatic joint vertically. (Cuellar, Smit, Zadpoor, et al., 2018)

Tilting the joint up to 45° is possible, but more tilt results in rougher surface finish and more friction in the joint. A way around this is with down-skin.

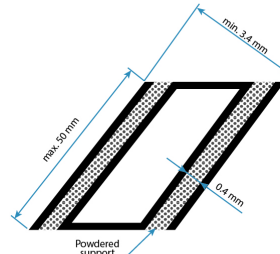
Printing horizontally is not recommended because of the support that is required. The sizing thresholds will also be different because of the 5 mm required opening to remove the support structures (Kumke et al., 2016). If the joint must be printed this way it is important to consider the profile of the joint's cross section. The cross section must be self supporting to not require support structures. That means that every angle must be more than 45° (Khademzadeh et al., 2023).

Print orientation	Size	Clearance	Support	Function
0°	Min 3.2 mm diameter	0.2 mm	Not required	Most optimal
45°	Min 3.4 mm diameter. Max 50 mm long.	0.2 mm (vertical surfaces). 0.4 mm (tilted surfaces).	Not required	
90°	Min 6 mm	0.4 mm	Required	Least optimal

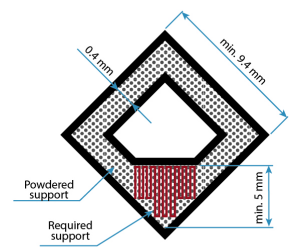
0° Print orientation



45° Print orientation



90° Print orientation



Options for redesign

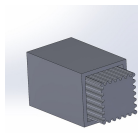
Worm shape

Pros:

- Easier powder removal
- Lower friction
- Less powder adhesion
- Support free

Cons:

- Can be difficult in some print orientations



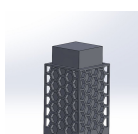
Cage Design

Pros:

- Easier powder removal
- Lower friction
- Less powder adhesion

Cons:

- Lower structural integrity



Sources

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- Khademzadeh, S., Zhou, Y., & Persson, C. (2023). Additive manufacturing of functional mechanical mechanisms using micro laser powder bed fusion.



Non-assembly mechanism

- Cylindrical joints
- Revolute joint
- Prismatic joint
- Helical joint**
- Spherical joint
- Redesign

Helical Joints

Metal AM Design Guidelines



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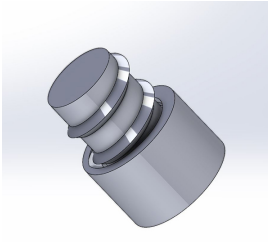


Fig 1: Ordinary helical joint

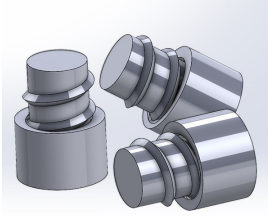


Fig 2: Helical joints in multiple built orientations

Description

Helical joints (sometimes referred to as screw joint, screw pair or helical pair) consist of two bodies joined together, allowing for both translational and rotational motion. The shape of the joint restricts the movement of the bodies to a specific rotational path, meaning that it is fixed in all angles except one, thereby enabling motion in one DOF (COMSOL, 2018). The translation length is coupled with the rotation angle by a linear equation (Ahmadinezhad et al., 2015). One common example of a helical pair is a bolt and a nut.

Clearance

The core in the helical joint is similar to a cylindrical joint and can therefore have the same clearance. The difference is the threads. Depending on their shapes and angles they need to have a different clearance (Thomas, 2009). Downskin can be used to improve the clearance overall.

Application

Helical joints are very similar to cylindrical joints with the addition of threads. (Ahmadinezhad et al., 2015) To adjust the relation between rotation and linear motion in the joint, it is the pitch that should be altered.

It can be difficult to manufacture a screw that should be used with a standard bolt or vice versa. The printer can not meet the tolerance requirements of the standard manufactured threads without post processing. It is therefore recommended to run a tap over the screw or bolt if they should be used for that purpose. (Thomas, 2009)

For less powder adhesion and less friction it is good to lower the contact area inside the joint by either dividing the slot into multiple segments or applying a redesign. For example, hemisphere design. (Kranz et al., 2015)

Support

Support structures should never be used on the inside of the joint (Thomas, 2009). The support requirements are similar to the cylindrical joint with one key difference. The threads. It is important to make sure the threads do not need any support structures. This can be done by altering the shape of the threads or the print orientation.

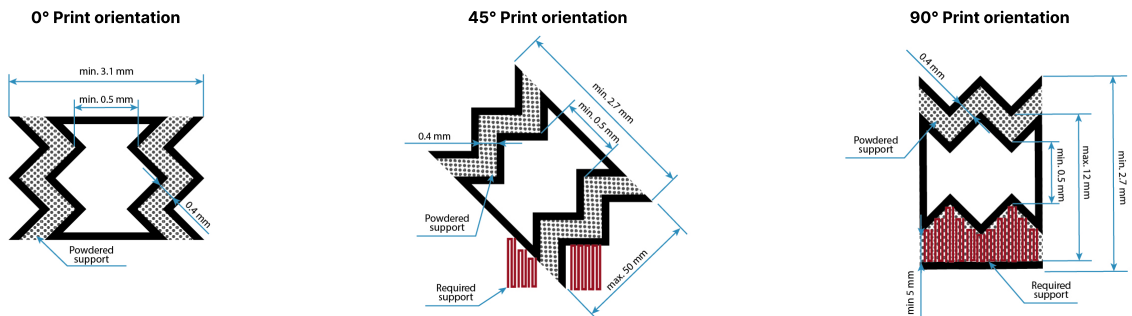
There will be powder support in the gaps that needs to be removed for optimal performance. Removing powder support becomes easier by increasing the clearance or by implementing a hemisphere design. A cage design can also help but due to the increased complexity in the geometry with the threads present, this is not recommended first hand.

Print Orientation

To manufacture in the 0° direction is the most optimal for the same reasons as for cylindrical joints. This also means that it can be tilted 45°. One additional thing to consider is the threads. It is important to make sure they are self supporting so they do not adhere to the socket.

The biggest challenge is to manufacture in 90°. The support structures that are required inside the joint needs a 5 mm hole to remove them (Kumke et al., 2016). The self supporting holes redesign may also need to be applied if the joint is large enough. It is important to notice that when doing this, the thread contact gets smaller and smaller. It is therefore important to make sure that there are enough thread contacts at all times to not prevent the function.

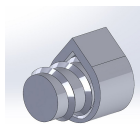
Print orientation	Size	Clearance	Support	Function
0°	Min 2.7 mm diameter	0.2 mm (core). 0.4 mm (threads)	Not required	Most optimal
45°	Min 2.7 mm diameter. Max 50 mm long.	0.4 mm (core). 0.4 mm (threads)/td>	Not required	
90°	Min 2.7 mm diameter. Max 12 mm inside diameter.	0.4 mm (core). 0.4 mm (threads)	Required	Least optimal



Options for redesign

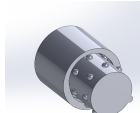
Self Supporting Holes

- Pros:
- Possible to print larger joints ant 90° without support
 - Lower friction
- Cons:
- Lower translational strength
 - Larger joint



Hemisphere

- Pros:
- Easier powder removal
 - Lower friction
 - Less powder adhesion
- Cons:
- Lower translational strength



Sources

COMSOL. (2018). Modeling mechanical systems in the multibody dynamics module [software documentation]. version 5.5. https://doc.comsol.com/5.5/doc/com.comsol.help.mbd/mbd_ug_modeling.3.07.html

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Non-assembly mechanism

- Cylindrical joints
- Revolute joint
- Prismatic joint
- Helical joint
- Spherical joint
- Redesign

Spherical Joints

Metal AM Design Guidelines



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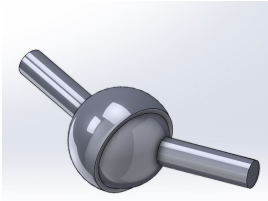


Fig 1: Ordinary spherical joint

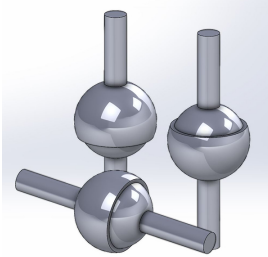


Fig 2: Spherical joints in multiple built orientations

Description

Spherical or ball joints have three rotational DOF and none translational. They consist of a ball that freely rotates inside a socket. The opening in the socket needs to be large enough to allow the ball to rotate and small enough to keep the ball inside. (COMSOL, 2018)

Clearance

Because of the spherical shape, the clearances will not differ depending on print orientation. Not enough clearance will result in powder adhesion, and the joint will not work. A too large clearance will result in an unstable joint. Down-skin can be used to lower the clearance. (Khademzadeh et al., 2023)

Application

The opening in the socket limits the rotation of the joint. The shape of the opening can be adjusted to limit the angles allowed in certain directions. Because the opening in the socket must be smaller than 180° degrees to keep the ball in, changing the hole shape to an oval, the allowed rotation angles can be improved to more than 180° in some directions. (Mavroidis et al., 2000)

Ball joints can be combined with other joints to create other, more complex joints. For example, two spherical joints connected with a rod will result in a distance joint. Putting a ball joint in a prismatic joint will result in a slot joint. (COMSOL, 2018)

To reduce the friction and powder adhesion in the joint it is important to lower the contact area inside the joint. One way to do this is to divide the socket into segments (Kranz et al., 2015), or apply a design principle such as a cage or worm design.

Support

Sintered support inside the joint can be hard to get out. If possible it should be avoided (Thomas, 2009). This can be done adjusting the print orientation or applying design principles.

There are print orientations where no support is required, for example in 180° degrees. If support structures are required at first glance, but because of the spherical shape, they can usually be ignored due to the difficulties in removing them. The best way is to use the down-skin principle (Khademzadeh et al., 2023). Otherwise there is a risk of dross and powder adhesion so the clearance has to be increased.

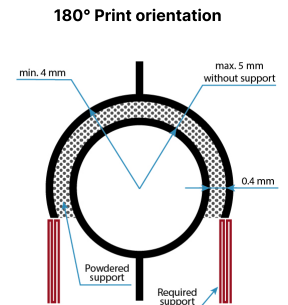
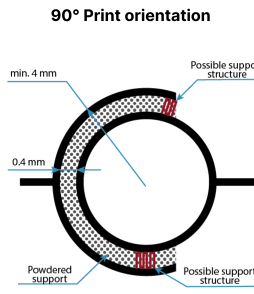
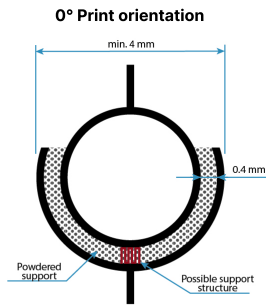
There will also be powdered support stuck inside the joint which can be difficult to remove (Cali et al., 2012). To get rid of that, the use of design principles such as cage or worm can be applied.

Print Orientation

When choosing a build orientation the goal is to minimise support structures inside the joint. All orientations are possible but some are better at minimising the need for support. Printing in the orientation 180° is the only way to print without support on the inside. This only applies if the joint is small enough to create the self-supporting radius that is the socket 6 mm (Kranz et al., 2015) or the self supporting holes principle is applied.

The other print orientations require support at first glance, but necessary precautions should be taken to avoid it.

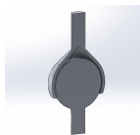
Print orientation	Size	Clearance	Support	Function
0°	Min 2 mm diameter	0.4 mm	Not required	
90°	Min 2 mm diameter. Max 12 mm inside diameter.	0.4 mm	Not required	
180°	Min 2 mm diameter. Max 12 mm inside diameter.	0.4 mm	Not required	Most optimal



Options for redesign

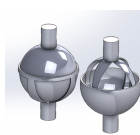
Self Supporting Holes

- Pros:
- Possible to print larger joints at 90° without support
 - Lower friction
- Cons:
- Larger joint



Cage Design

- Pros:
- Easier powder removal
 - Lower friction
 - Less powder adhesion
- Cons:
- More complex design
 - Lower structural integrity



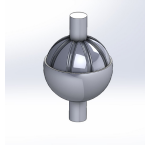
Worm shape

- Pros:
- Easier powder removal
 - Lower friction

Less powder adhesion

Cons:

More complex design



Sources

COMSOL. (2018). Modeling mechanical systems in the multibody dynamics module [software documentation]. version 5.5.

https://doc.comsol.com/5.5/doc/com.comsol.help.mbd/mbd_ug_modeling.3.07.html

Thomas, D. (2009). The development of design rules for selective laser melting (version 1). (Doctoral dissertation). Cardiff Metropolitan University.

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<https://doi.org/https://doi.org/10.2351/1.4885235>

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Cali, J., Calian, D. A., Amati, C., Kleinberger, R., Steed, A., Kautz, J., & Weyrich, T. (2012). 3d-printing of non-assembly, articulated models. *ACM Transactions on Graphics*, 31(6), 1–8. <https://doi.org/https://doi.org/10.1145/2366145.2366149>



Non-assembly mechanism

- Cylindrical joints
- Revolute joint
- Prismatic joint
- Helical joint
- Spherical joint
- [Redesign](#)

Redesigns

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When manufacturing joints with AM, there are several aspects that have to be taken into consideration, such as support removal and powder extraction. To address these challenges, design modifications could be necessary depending on the specific situation and joint. The following sections describe the most general approaches for altering joint designs. These approaches are applicable to most types of joints.

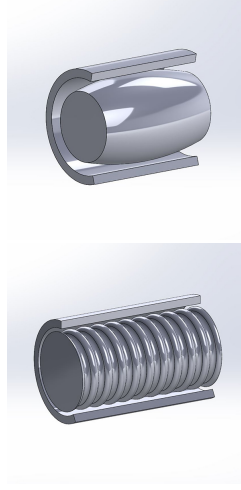
Drum and worm shape

Drum-shaped design is considered to be one of the most optimal ways to construct a revolute joint with low clearances. Constructing the pin in a drum shape, where the radius decreases from the middle towards each end. Since large joint clearances lead to vibrations and instability this is an important part of making functional AM joints. By constructing the joint with an increased gap, towards the openings, it makes for a simpler powder extraction and support removal (Cuellar et al., 2018).

Another design principle for revolute joints or other joints with adjacent surfaces is the use of worm design. Worm design is the use of evenly distributed teeth along the axis of the pin. The teeth of the worm are cylindrical and not helical with a set dimension of width and number of teeth (Wei et al., 2016).

The main benefit with using the worm-shape is that sintered supports are no longer required in most build orientations. During testing made by Wei et al. (2016) it was determined that as long as the slope of the teeth is greater than 45°, seen from the axle, the geometry will be self-supporting during manufacturing.

Worm-shaped design outperforms both normal-shaped and drum-shaped designs due to its smooth operation and relatively low amount of vibration. Because of the effective mitigation of vibration, the worm-shape also performs well with asymmetric loads. This correlation can be applied to most joints; low vibrations, i.e. tighter clearance, leads to an increased dynamic performance (Wei et al., 2016).



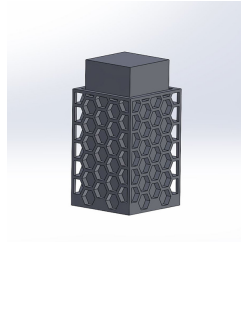
Cage Design

Cage design implies that the entire or a portion of the joint is designed similar to a cage or mesh. The main inspiration for this comes from Cali et al. (2012), where different types of cage designs for ball joints were explored. Their conclusion was that all the different designs were functional.

The gaps in the cage allows for easier support removal as well as a way for powder to escape, while the lower surface area gives lower friction. Additionally, sintered support can be built through the mesh to support structures on the other side. This allows for such support structures to be removed easier and they will not be connected to the inside of the joint improving its surface (Cali et al., 2012).

Another positive aspect of cage design is that it can be applied in almost every type of model, even if it is not a joint. Advantages that apply to all structures are lowered weight and material usage. In that way, the manufacturing cost is brought down (Cali et al., 2012).

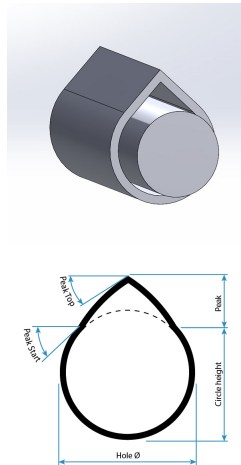
There are two main aspects to consider before applying a cage design. The first is complexity. It is a lot more complex to design an AM lattice structure than a solid model. Secondly is stability. A lattice structure will for obvious reasons not have the same structural integrity as a solid part of the same size. Apart from the structure being overall weaker, depending on the design, the lattice structure will have anisotropic mechanical properties that need to be considered before application (Stanković et al., 2017).



Self supporting holes

When manufacturing holes with PBF-LB, build orientation is an important aspect. Building vertical holes can be challenging, especially without the use of support structures. Tests made by Thomas (2009) show that larger holes start to distort downwards at the top. Kranz et al. (2015) claim in their design guidelines that holes without support can successfully be built up to 12 mm in diameter. Holes larger than that can be built with support structures, but they can be difficult to remove. Instead, Thomas (2009) presents a redesign solution.

By adding a self-supporting peak to the hole, the risk of sagging is greatly removed. Thomas (2009) presents values for holes with sizes ranging from 2 mm up to 30 mm, as shown in the table below. It is claimed that the values in the table are optimised to maximise the circle circumference and minimise the peak height.



Hole Ø	Circle Height	Peak	Peak start	Peak top
2 mm	1.85 mm	0.3 mm	31.69°	28°
4 mm	3.38 mm	0.95 mm	38.52°	28°
6 mm	5.63 mm	0.95 mm	38.52°	28°
8 mm	7.31 mm	1.66 mm	45.05°	28°
10 mm	8.95 mm	2.6 mm	51.98°	28°
12 mm	10.58 mm	3.7 mm	47.32°	28°
14 mm	12.22 mm	4.58 mm	48.94°	28°
16 mm	13.97 mm	5.325 mm	45° Angle	n/a
18 mm	15.76 mm	5.942 mm	45° Angle	n/a
20 mm	17.36 mm	6.769 mm	45° Angle	n/a

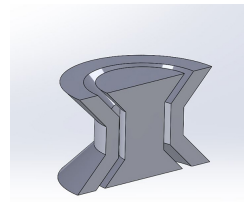
22 mm	18.96 mm	7.591 mm	45° Angle	n/a
24 mm	20.63 mm	8.338 mm	45° Angle	n/a
26 mm	22.27 mm	9.114 mm	45° Angle	n/a
28 mm	23.76 mm	10.04 mm	45° Angle	n/a
30 mm	25.4625 mm	10.75 mm	45° Angle	n/a

Tilting stops

A stop can be required on joints that risk slipping out of their sockets when they are in use. The main joints this applies to are prismatic, cylindrical, and revolute joints. Manufacturing parts similar to a washer at the end of a socket can be complicated because of the support requirements both inside the joint and next to the washer.

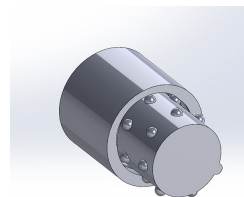
The tilting stops redesign is a way to manufacture the stops at an angle so that they can be manufactured without support structures and still be fully functioning. From Kranz et al. (2015) paper on design guidelines and observing the different build orientation of mainly revolute joints, a configuration that worked was found.

As shown in figure below, the stops in the revolute joint should be tilted like a cone to still allow rotation and prevent translation. The angle can vary but the suggested angle is 45°. The importance is that the stop is self-supporting everywhere on the model. The clearance between the stop and socket should be 0.4 mm because of the angled surface.



Hemisphere

Detta är en text om Hemisphere

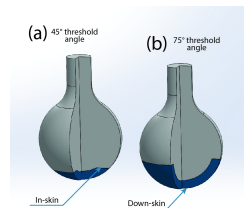


Down-skin

The body of the manufactured model can be broken down into two parts: the down-skin and the in-skin, i.e. the regular build. Down-skin is explained as: "The term 'Down-skin' is used for such downward overhanging surfaces of a part that is not supported during building neither by previously solidified layers nor the building platform at the bottom. Instead, the melt pool in the down-skin area is supported by unfused powder particles" (Khademzadeh et al., 2022, p. 2).

The AM company EOS released a technology that made manufacturing without support easier. They call it Smart Fusion (Wohlfart, 2022). The essence of Smart Fusion is that it lowers the power when there is a risk for powder adhesion. Khademzadeh et al. (2022) used the same principle to lower the power on the down-skin to get lower dross formation. The experiments demonstrated that a ball joint with a clearance of 0.2 mm and down-skin applied on a 75° threshold angle gave a successful joint.

This down-skin principle can be applied to all joint types. This can lower the required clearance to 0.2 mm everywhere because of the decreased dross. EOS claims that the Smart-fusion can manufacture down to 13° without support compared to the previous 45° standard (Wohlfart, 2022). It is therefore not recommended to use the down-skin principle to manufacture large flat horizontal down-skin areas without support.



References

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A.2 Polymer print prototypes

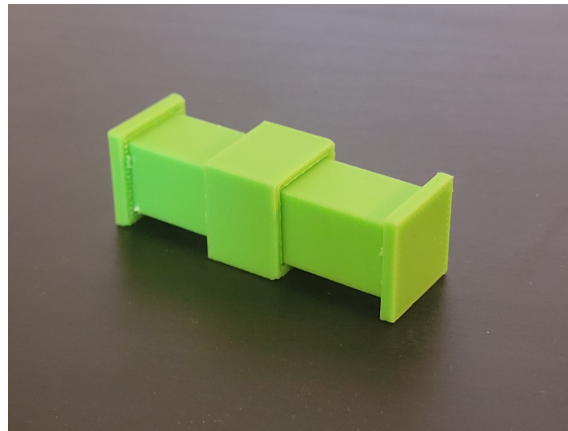


Figure A.1: Ordinary prismatic joint

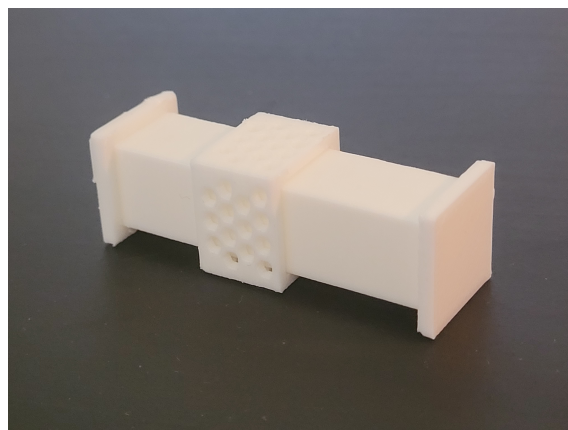


Figure A.2: Prismatic joint, cage design

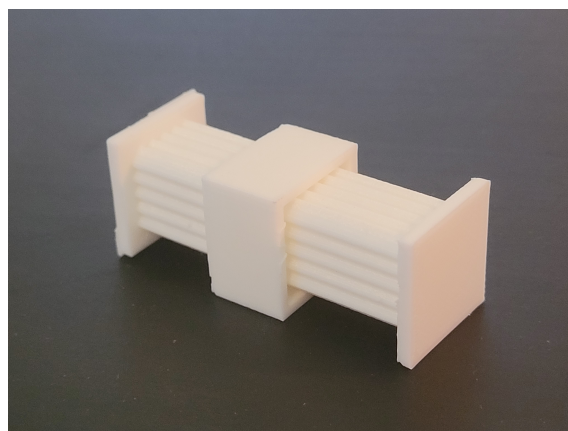


Figure A.3: Prismatic joint, worm design



Figure A.4: Ordinary cylindrical joint



Figure A.5: Cylindrical joint, self supporting hole

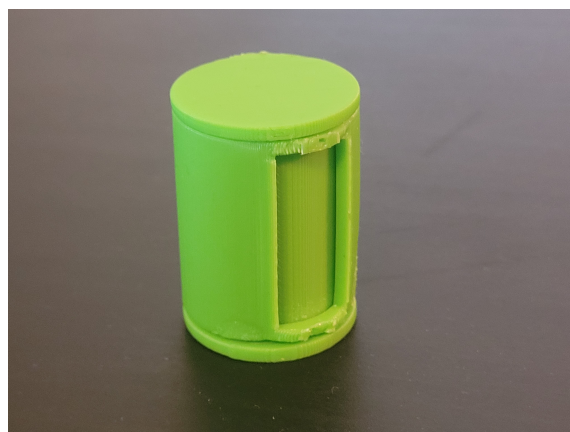


Figure A.6: Ordinary revolute joint

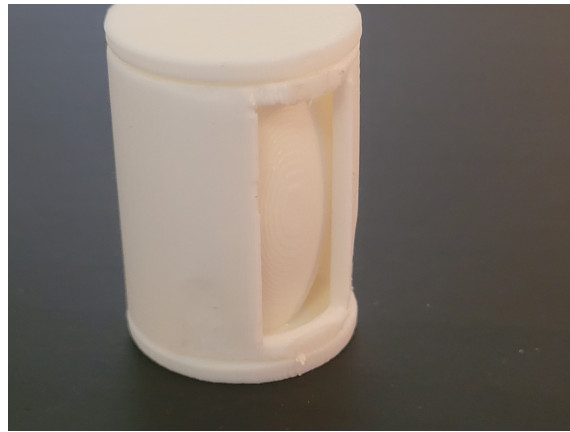


Figure A.7: Revolute joint, drum design



Figure A.8: Revolute joint, worm design



Figure A.9: Revolute joint, tilted stops



Figure A.10: Ordinary spherical joint



Figure A.11: Spherical joint, cage design



Figure A.12: Ordinary helical joint

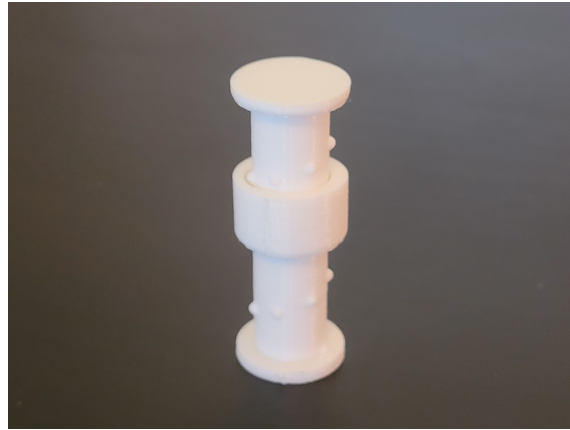


Figure A.13: Spherical joint, hemisphere design

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