FDM 3D-PRINTING FOR SHAPE MEMORY PURPOSES

A guide for printing shape memory objects using PLA

By Jesse Holierhoek

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DESIGNING 3D-PRINTED DEPLOYABLE STRUCTURES WITH SHAPE MEMORY POLYMERS

INTRODUCTION

This document serves as a tool for designers to support them in designing 3D-printing shape memory objects. The shape memory effect refers to the ability of certain materials to ''remember'' a specific shape they were trained to adopt, and retrieve this shape when being exposed to an external stimulus after deformation. The stimulus needed to activate shape recovery is material dependent, with the most common stimulus being temperature. Shape memory materials (SMM's) can be classified as conventional materials: metals, polymers, ceramics and composites. The occurrence of the shape memory effect in polymers was first discovered in 1941 by Vernon et al. Since then, SMP's have slowly gained attention from researchers and they have been applied in different fields.

3D-printing is a promising production technique for creating SMP objects. 3D-printing, or additive manufacturing, is the process of constructing a three-dimensional object from a digital file. In recent years, additive manufacturing has gained the attention of the general public, with a great deal of hobbyist printers being available for use at home, and high-end printers being used in industry to produce products ranging from consumer goods to prosthetics, tools, and parts used in the automotive industry. The most common and well-known type of additive manufacturing is material extrusion, often referred to as Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF) (in this document, FDM will be used to refer to this method). This method uses a filament spool which is supplied to an extrusion nozzle where it is heated and extruded. Through relative movement of the extrusion nozzle and the build-plate, a layer of material is formed. Additional layers are printed on top of this in the same manner, creating a 3D-object.

Where 3D-printing was first only used for prototyping and one-off manufacturing in early stages of the process, it is rapidly developing to become a proper production method. As was mentioned, is also a promising production technique for SMP objects. The ability to change shape gives 3D-printed SMP objects great potential for a wide variety of applications.

GUIDELINES INTRODUCTION

There are a significant number of parameters influencing the functionality of 3d-printed shape memory objects. For successfully 3d-printing shape memory objects with predictable shape memory behaviour, these parameters need to be considered. This document describes the effect of these parameters on the shape memory behaviour of FDM 3D-printed SMP objects in the form of guidelines. These guidelines are meant to help designers to design and manufacture SMP objects using FDM 3D-printing.

Each of the guidelines addresses one parameter related to 3D-printing shape memory polymer objects. The guidelines are divided into 4 different groups, related to different stages in product development: Design, Material, Manufacturing and Use. Each group discusses the evaluated parameters involved in this stage of the process, by explaining the parameters and assessing their influence on three shape memory aspects:

SELF-DEFORMATION

Self-deformation refers to the tendency of shape memory materials to deform from its printed shape when exposed to an external stimulus, without an external force acting on it. This is caused by internal stresses that get trapped in the material when the material cools down during printing. Depending on the application, self-deformation can be desirable or undesirable.

SHAPE RECOVERY

Shape recovery refers to the ability of a material or object to recover to its printed shape after deformation. This is linked to self-deformation in the sense that objects which display a high degree of self-deformation generally display bad shape recovery to the printed shape (larger deviation from the printed shape after recovery).

ACTIVATION TIME

Activation time refers to the time it takes for the printed object to start the shape recovery process after being exposed to an external stimulus. Parameters that influence activation time can also be utilized to achieve sequential shape change within an object. By having different values for a specific parameter in different parts of an object, the activation for the different parts will vary, meaning that some parts will start the recovery earlier than other parts.

LITERATURE AND TESTING

For each guideline, the literature sources on which that specific guideline is based are mentioned at the bottom right of the page. The tested values for the parameter are specified as well, to provide some context on the origin of the guideline, and to provide the reader of this document an indication under which circumstances the effect of each parameter is expected to be as described in the guideline. At the end of this document, the complete sources are listed, should further information on the testing method or the results be needed.

Apart from being based on literature, certain parameters described in the guidelines were tested as part of the graduation project which this document is a part of. This is indicated also at the bottom right corner of each guideline, as ''testing''. As is also the case for the literature sources, the tested values are specified to provide some context for the reader. For more information on the project, please contact one of the people involved via the e-mail addresses listed on page two of this document.

CONSIDERATIONS REGARDING THE GUIDELINES

These guidelines were developed to be used for 3D-printing shape memory polymers. However, the shape memory effect is an inherent ability of most polymers, although the degree to which different materials possess this ability differs. These guidelines were written for printing shape memory objects using Polylactic Acid (PLA). For establishing the guidelines, this material was used to print test samples to test the different parameters. Also, literature referred to in this document is mainly focused on 3D-printing with PLA. This material is activated by heating the material above its glass transition temperature: +/- 60-65°C. Therefore, these guidelines might not hold true when 3D-printing with a different material. This should be considered when using these guidelines.

The guidelines described in this document were developed as part of a graduation project, by combining knowledge gained through literature research and parametric testing. However, due to the complexity of the subject and the limited time span of the project, this document is not a complete guide to 3D-printing shape memory objects. Certain parameters discussed in this document have not been fully researched. The unknown effect certain parameters have on specific shape memory aspects are indicated as ''unknown'' in the document.

Furthermore, two important aspects related to the shape memory effect will not be actively discussed in the guidelines, with the first one being shape fixity. This aspect refers to a materials ability to retain its shape in the deformed state. In the experiments performed to establish the guidelines, the PLA test samples displayed excellent shape fixity, with no spring back being observed after deformation and cooling, regardless of parameter values. The second aspect is cycle life, which refers to the amount of shape memory cycles a shape memory object can go through before it fails/starts displaying inadequate shape memory capabilities.

GLOSSARY

In the guidelines, certain terms related to 3D-printing and the shape memory effect are used. These terms are explained below:

Active parts – parts of the object made of shape memory material, that are meant to be deformed and are able to recover their original shape.

Passive parts – parts of the object not made of shape memory material, that are not intended for deformation and shape recovery.

Glass transition temperature – the temperature at which a material switches between its glassy and rubbery state: the point at which a shape memory material activated through heat can be deformed or start recovering its original shape

Printed shape – the original shape of the object

Temporary shape – a deformation from the printed shape above the glass transition temperature of the material, caused by external forces. The shape memory material can be fixed in this shape when the material is cooled below its glass transition point while the deformation is maintained. Once heated above the glass transition temperature, the material will try to recover, and the temporary shape will be lost

Sequential shape change – the phenomenon which occurs when there are multiple active areas in a shape memory object, which have different activation times

Positively bended – a (shape memory) hinge part which is deformed in the same direction as in which self-deformation occurs

Negatively bended – a (shape memory) hinge part which is deformed in the opposite direction as in which self-deformation occurs

ICON EXPLANATION

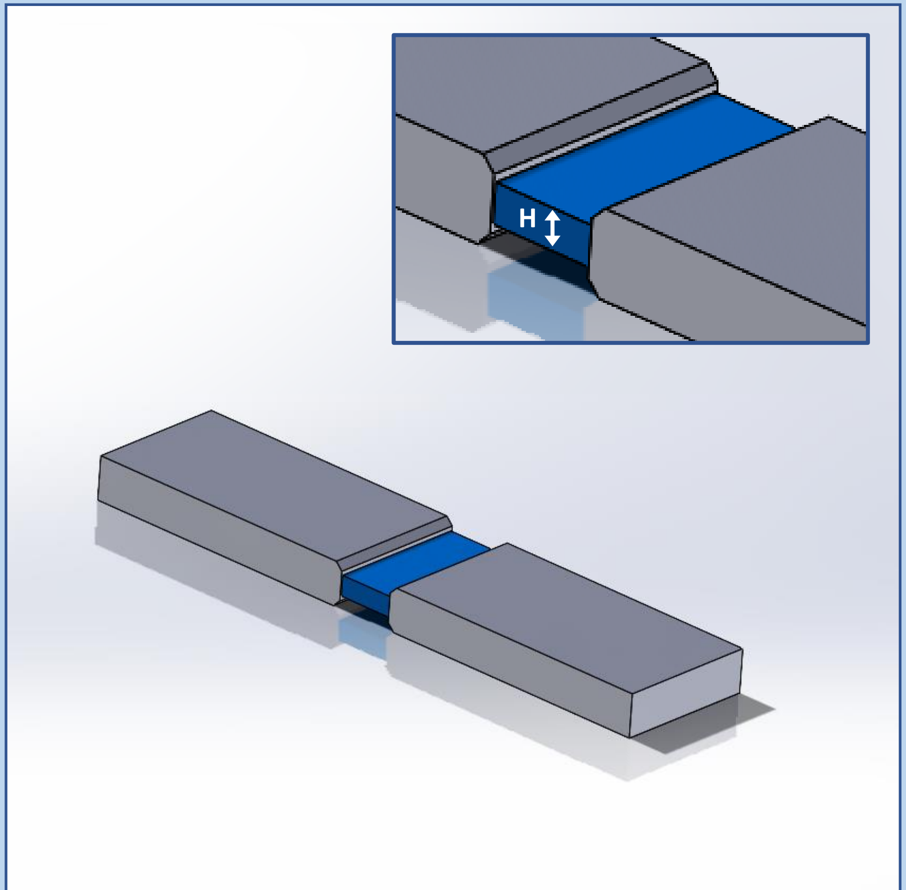
In the guidelines, several different icons are used to visualize the effect a parameter has on the three shape memory aspects described earlier in this document (self-deformation, shape recovery, and activation time). In the table below, the meaning of these different icons is explained.

Symbol	Meaning
⇧	Increasing the value of the parameter described in this guideline increases/improves this shape memory aspect.
⇩	Increasing the value of the parameter described in this guideline decreases this shape memory aspect.
✓	The parameter described in this guideline has an effect on this shape memory aspect. However, this parameter cannot be expressed as a numerical value (for example, material choice), so it can't be specified how the chosen value for this parameter will influence this shape memory aspect.
✕	The parameter described in this guideline has no effect on this shape memory aspect.

DESIGN

MATERIAL THICKNESS

Material thickness refers to how thick the shape memory material is in a cross section of the designed object. For both the active and inactive parts of a printed object, material thickness has an influence on the functioning of the object. In the figure below, this definition of material thickness is illustrated.

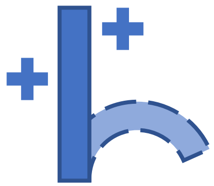


Material thickness H illustrated with a simple sample with two inactive parts connected by an active hinge part (blue).

SELF-DEFORMATION

Increasing material thickness decreases self-deformation. By increasing the thickness of the material, it prevents itself from self-deforming due to the print becoming more rigid.

SHAPE RECOVERY



Increasing material thickness improves shape recovery to the original shape. Self-deformation decreases, so the material has less internal stresses.

ACTIVATION TIME

Increasing material thickness increases the activation time. For the material to activate, it needs to be heated above its glass transition temperature. Increasing the material thickness increases the amount of material, thus more time is needed to heat it above the glass transition temperature. Depending on the precise way of heating and material thickness, differences in terms of seconds can be noticed.

<u>Literature</u>

Mehrpouya et al. (2020): 0.9 – 1.5 mm material thickness for the active areas

Esfahani (2021): 1.5 - 2.5 mm material thickness

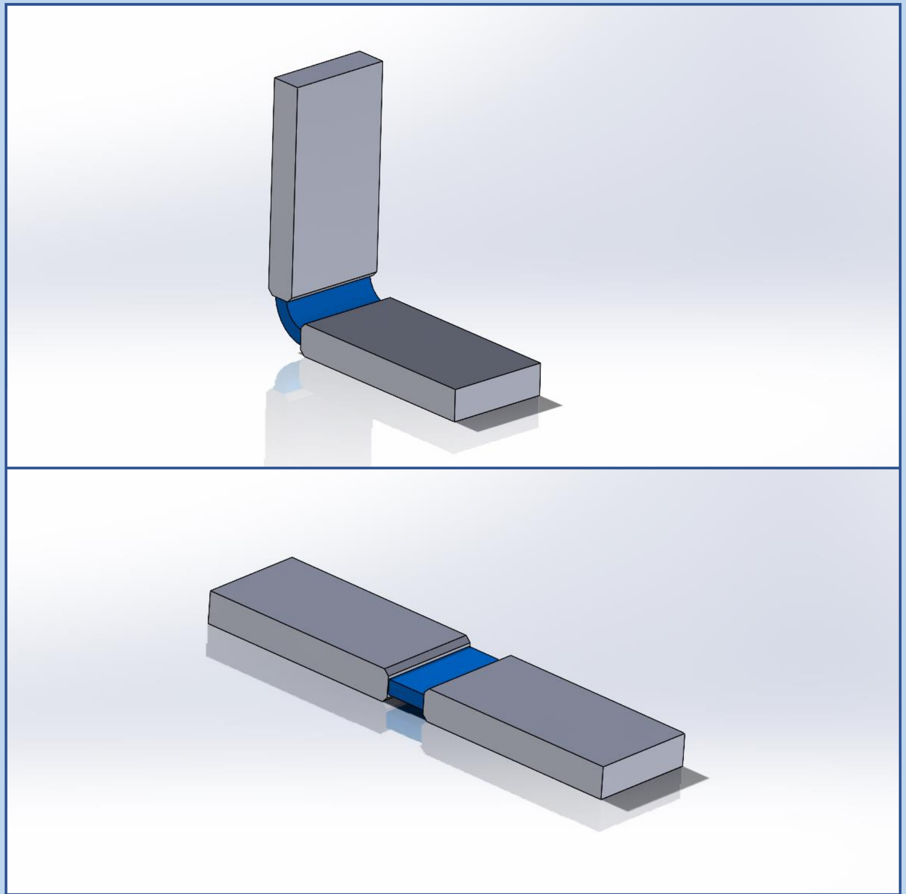
<u>Testing</u>

0.8 – 1.4 mm material thickness for the active areas

DESIGN

PRINT CONFIGURATION

Print configuration refers to the state in which an object is printed. A distinction is made between two configurations: 3D, meaning that the object is printed in its deployed state, and 2D, meaning that the object is printed in a flat state. This is illustrated in the figure below. Either configuration might be suited for your print, depending on the envisioned functioning of the object.

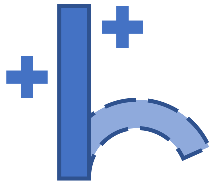


Examples of a simple object in a 3D-configuration (top) and a 2D-configuration (bottom).

SELF-DEFORMATION

This parameter has no significant effect on self-deformation, meaning that 2D and 3D printed samples will display similar self-deformation, given that the values for other parameters remain the same. This can be explained by the fact that the geometry of the printed object does not change in terms of dimensions or printer settings, only the printed and temporary shapes are switched.

SHAPE RECOVERY



This parameter has no significant effect on shape recovery, meaning that 2D and 3D printed samples will display similar shape recovery, given that the values for other parameters remain the same. This can be explained by the fact that the geometry of the printed object does not change in terms of dimensions or printer settings, only the permanent printed and temporary shapes are switched.

ACTIVATION TIME

This parameter has no significant effect on activation time, meaning that 2D and 3D printed samples will display similar activation times, given that the values for other parameters remain the same. This can be explained by the fact that the geometry of the printed object does not change in terms of dimensions or printer settings, only the printed and temporary shapes are switched.

Literature

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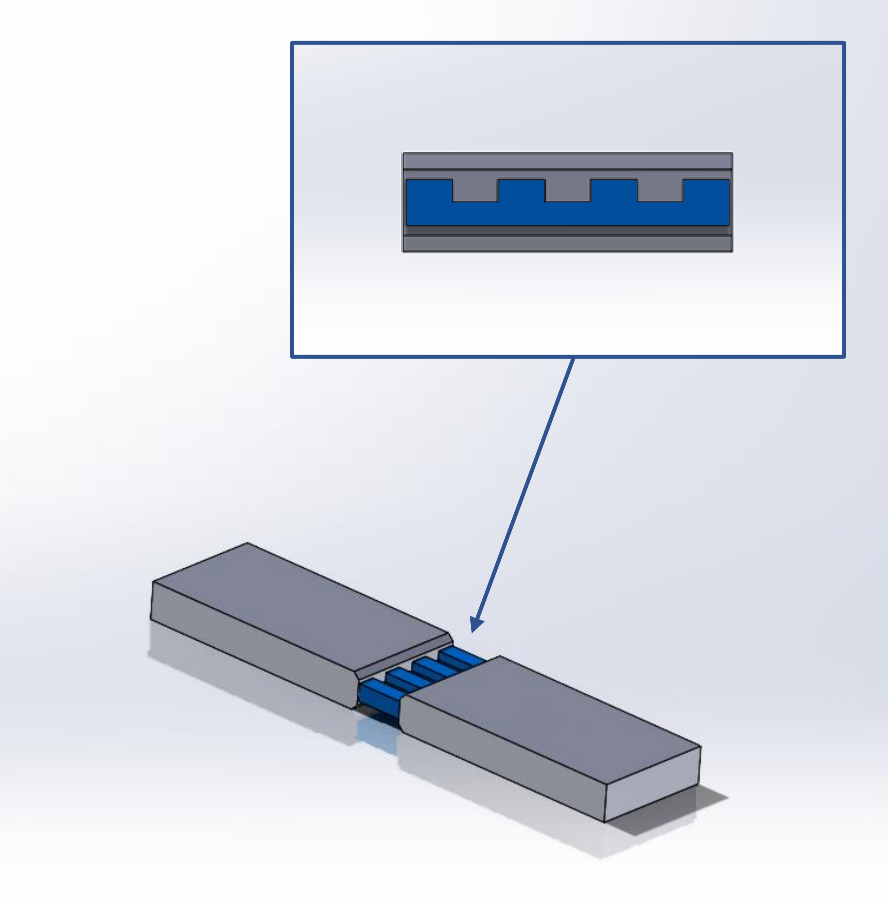
Testing

samples with an active part printed in 2D (flat) and 3D (90 degree angle) configuration

DESIGN

POROSITY

Porosity is a parameter related to the design of the active areas in a shape memory object. Simply put, it refers to the presence of grooves in the active parts: sections taken out of the active area in the width direction. This is illustrated in the figure below. By modelling grooves in the active areas, the surface area of the active part increases.

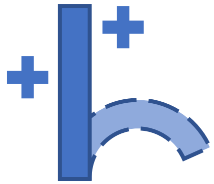


An example of grooves in the active area of a shape memory object, with the top right showing an enlarged cross section of the active area.

SELF-DEFORMATION

Unknown

SHAPE RECOVERY



Unknown

ACTIVATION TIME

By adding grooves in an active area, the surface area increases, and the amount of material decreases, which allows for easier heat penetration, leading to shorter activation times. This is a useful design tool to achieve sequential shape change. Increasing the number and depth of the grooves leads to faster activation.

Literature

Van Manen et al. (2017): different number and size of grooves in similar active areas

Testing

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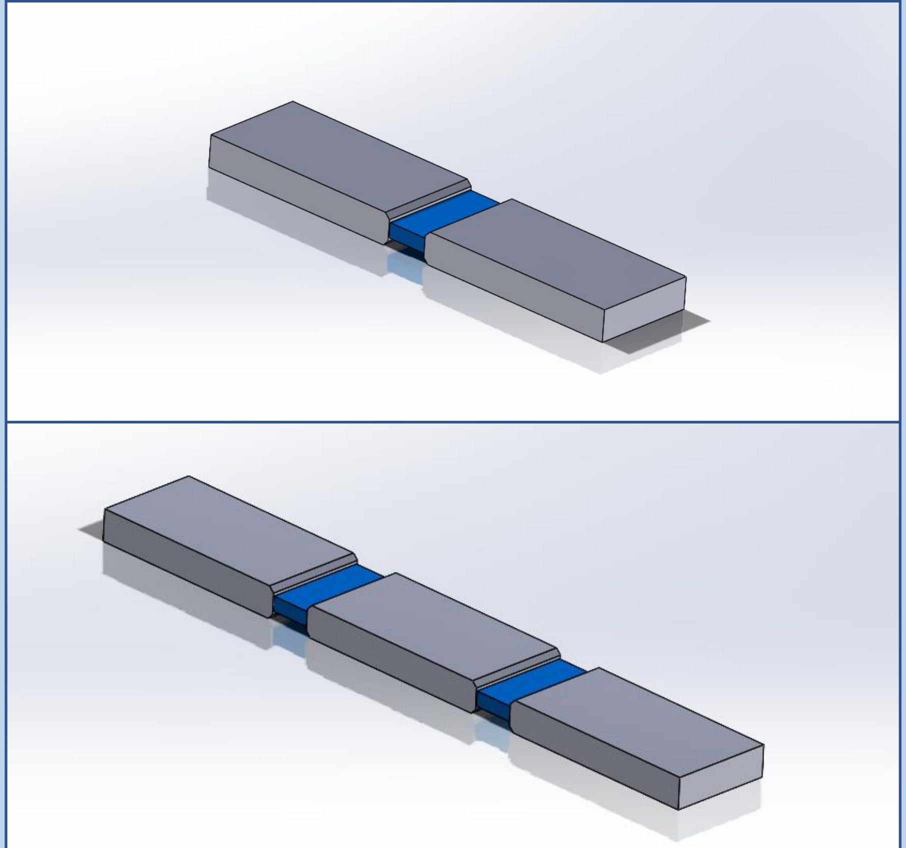
DESIGN

SHAPE COMPLEXITY

Shape complexity refers to how elaborate an object and its active parts are, with low shape complexity objects having fewer and simpler elements (active and passive parts) than objects with a high shape complexity.

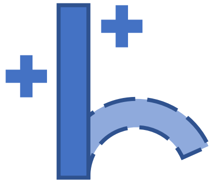


Example of a simple shape with two inactive parts and one active part (top), and a more complex shape with three inactive parts and two active parts (bottom).

SELF-DEFORMATION

Unknown

SHAPE RECOVERY



⇩

Increasing shape complexity leads to a slight decrease in shape recovery. Furthermore, increasing the shape complexity increases the likelihood of the object showing limited functionality.

ACTIVATION TIME

⇧

Shape complexity in itself does not necessarily have a significant influence on activation time. However, differences in activation time can occur, with more complicated shapes usually having longer activation times. However, this is dependent on the specific design of the object.

<u>Literature</u>

-

<u>Testing</u>

samples with one active part and two inactive parts compared to samples with two active parts and three inactive parts

MATERIAL

MATERIAL

This parameter refers to the specific type of material (in this case, specific type of PLA) used to manufacture the object. Differences in material properties and behaviour can occur between materials from different manufacturers, but also for different colours of the same material etc.

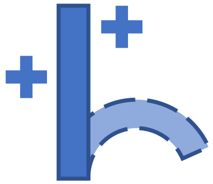
	Unit	Ultimaker	Makerpoint
Printing temperature	**(°C)**	200 - 210*	205 +/- 10
Melting temperature	**(°C)**	145 - 160	115 +/- 35
Glass transition temperature	**(°C)**	~ 60	57
Melt mass-flow rate	**(gr/10 min)**	6.09	9,56
Tensile stress at yield	**(MPa)**	49.5	70
Elongation at yield	**(%)**	3.3	5
Elongation at break	**(%)**	5.2	20
E-modulus	**(MPa)**	2346.5	3120
Impact strength	**(kJ/m^2)**	5.1	3.4

Two PLA filament types (Ultimaker PLA white and Makerpoint PLA signal white) meant for the same type of 3D-printer, made by different manufacturers (Makerpoint, n.d.). The differences in material properties for these materials are shown in the table (Ultimaker (2018) & Makerpoint (2019)).

SELF-DEFORMATION

Self-deformation is affected by the specific material used, with the extent to which self-deformation occurs being dependent on which specific material is used. It is not currently known which material properties influence this.

SHAPE RECOVERY



Shape recovery is affected by the specific material used, with the extent to which self-deformation occurs being dependent on which specific material is used. It is not currently known which material properties influence this.

ACTIVATION TIME

Activation time is affected by the specific material used, with the extent to which self-deformation occurs being dependent on which specific material is used. It is not currently known which material properties influence this.

Literature

Yu et al. (2015): different material compositions using a mixture of two different monomers (SLA printing)

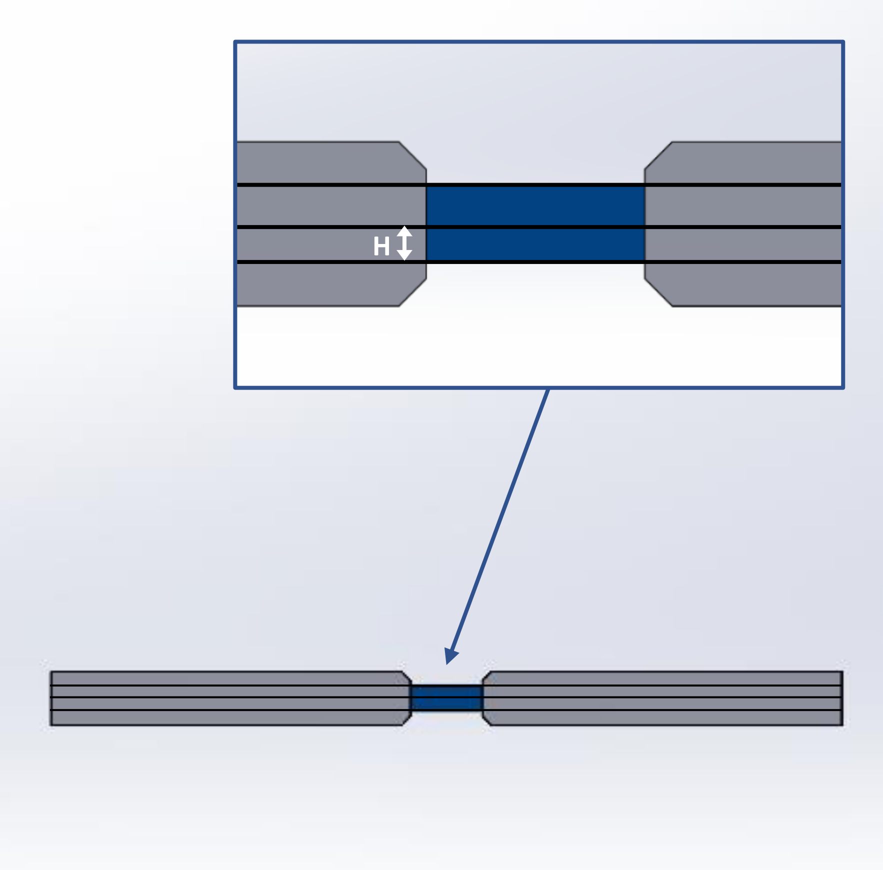
Testing

Ultimaker white filament compared to Makerpoint white filament

MANUFACTURING

LAYER HEIGHT

Layer height refers to the height of each printed layer, with higher values producing faster prints in lower resolutions, while lower values produce slower prints in higher resolutions.



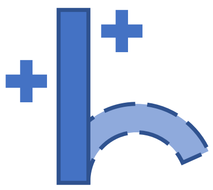
Side view illustration of a simple object, showing the different print layers.

SELF-DEFORMATION

⇩

By increasing the layer height, self-deformation decreases. Thicker layers take slightly longer to cool, giving the material a small amount of time to release some internal stresses during printing. Furthermore, the material gets less stretched during printing if the layer height is higher, further decreasing internal stresses in the printed material, thus decreasing self-deformation.

SHAPE RECOVERY



⇧

Shape recovery improves with an increased layer height. A higher layer height means there less layers that need to be printed to produce a certain object, reducing the imperfections in the material caused by printing, and increasing the material homogeneity. This positively affects the shape recovery of a printed shape memory object.

ACTIVATION TIME

⇩

By increasing the layer height, activation time is reduced somewhat. This is expected to be caused by a reduced amount of air gaps between printed lines and layers. Since air is a good insulator, it is difficult for heat to penetrate printed objects with a high number of air gaps. So, to reduce activation time, the number of air gaps needs to be reduced, thus, the layer height should be increased.

<u>Literature</u>

Mehrpouya et al. (2020): 0.15 - 0.3 mm layer height

van Manen et al. (2017): 0.05 - 0.2 mm layer height

<u>Testing</u>

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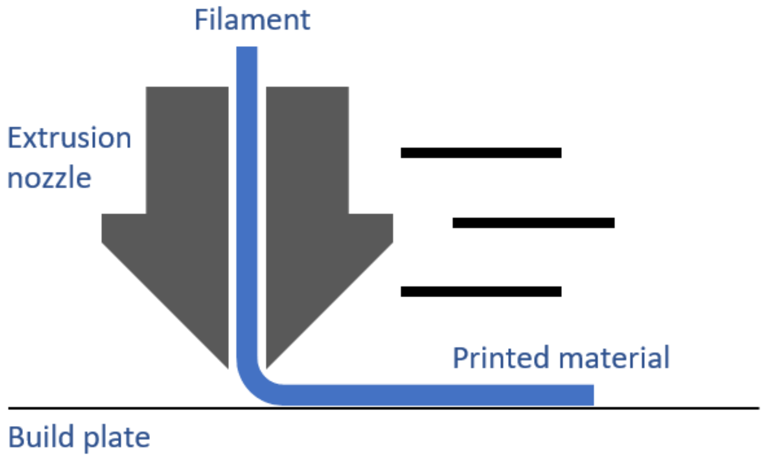
MANUFACTURING

PRINTING SPEED

Printing speed refers to the speed at which an object is printed. Printing speed determines the speed at which the nozzle moves around while printing, and the speed at which material is extruded. Increased printing speed decreases the time needed to print an object, but generally also decreases the surface quality and strength of the print.



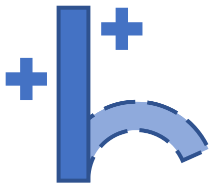
Schematic overview of the FDM printing process, indicating the most important components involved, with printing speed visualized by the black lines. Increasing printing speed means the nozzle will move faster, and material will be extruded faster.

SELF-DEFORMATION

⇧

By increasing the printing speed, self-deformation increases. Due to the higher printing speed, the material is stretched more, which leads to more internal stresses, thus more self-bending.

SHAPE RECOVERY



⇩

Since a higher printing speed leads to more internal stresses, it is expected that shape recovery to the printed shape will decrease. However, this has not been documented, so the extent to which printing speed affects shape recovery is unknown.

ACTIVATION TIME

Unknown

Literature

Esfahani (2021): 20 - 80 mm/s printing speed

Kačergis et al. (2019): 35-95 mm/s printing speed

Testing

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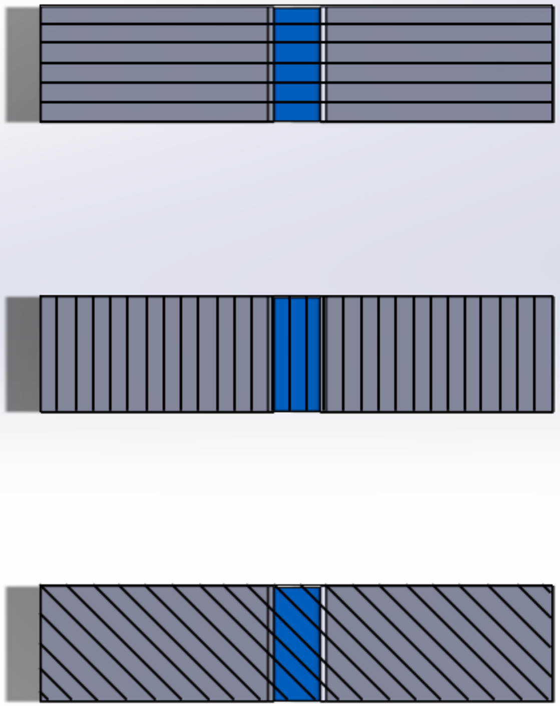
MANUFACTURING

INFILL LINE DIRECTION

Infill line direction determines in what direction the infill lines are printed. This direction can be changed for each layer, depending on the desired outcome.



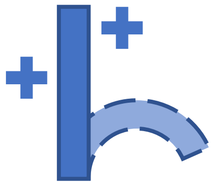
Top view of three samples illustrating different infill line directions.

SELF-DEFORMATION

✓

Self-deformation is affected by this parameter, with the effect depending on the specific values for this parameter. Infill line direction both influences the magnitude and direction of self-deformation. Printed lines shrink or expand in the longitudinal direction when cooled or heated. Therefore, if the infill line direction is all in one direction, a relatively high degree of self-deformation will occur, since all deformation happens in the same direction. To limit self-deformation, a solution is to alternate between different infill line directions for each consecutive layer e.g. have the first layer print with a 135° infill line direction, the second with a 45° infill line direction, the third layer 135° again, fourth layer 45° again etc.

SHAPE RECOVERY



✓

Shape recovery is affected by infill line direction, and is linked to self-deformation, meaning that the infill settings leading to increased self-deformation, will decrease shape recovery, while settings that limit self-deformation will lead to better shape recovery.

ACTIVATION TIME

Unknown

Literature

van Manen et al. (2017): Multitude of infill angles in different configurations: same direction for all layers, alternating between layers and alternating within a layer.

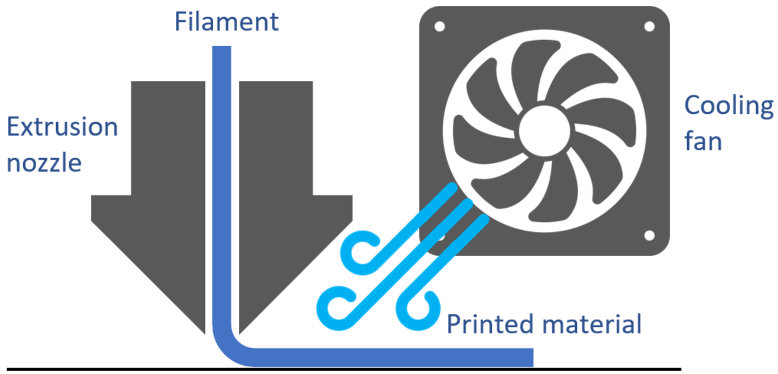
Testing

Line infill pattern under 45, 90 and alternating 45/135 degrees infill

MANUFACTURING

FAN SPEED

Fan speed refers to the speed at which the fan assigned to cool the printed material rotates. When setting up this parameter in slicer software, the speed is expressed in a percentage. A high fan speed leads to faster cooling, while a low fan speed leads to slower cooling of the printed material.

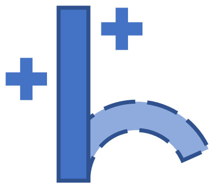


Schematic overview of the FDM printing process, indicating the most important components involved in the printing process, and the cooling fan which cools the printed material. This fan is attached close to the print head, enabling it to cool the material immediately after it has been printed.

SELF-DEFORMATION

By increasing the fan speed, self-deformation slightly increases. This is due to the material cooling faster, which gives the material less chance to already lose some of its internal stresses during the cooling process.

SHAPE RECOVERY



Shape recovery slightly decreases with an increased fan speed, based on the effect on self-deformation, although in practice, this effect is not significant.

ACTIVATION TIME

By increasing the fan speed, activation times become slightly longer. The exact reason why this is the case has not been documented. However, it can be reasoned that with faster cooling, the printed material has less time to flow, leading to slightly bigger air gaps in the printed object, which increases activation time.

Literature

Esfahani (2021): 50% and 100% fan speed

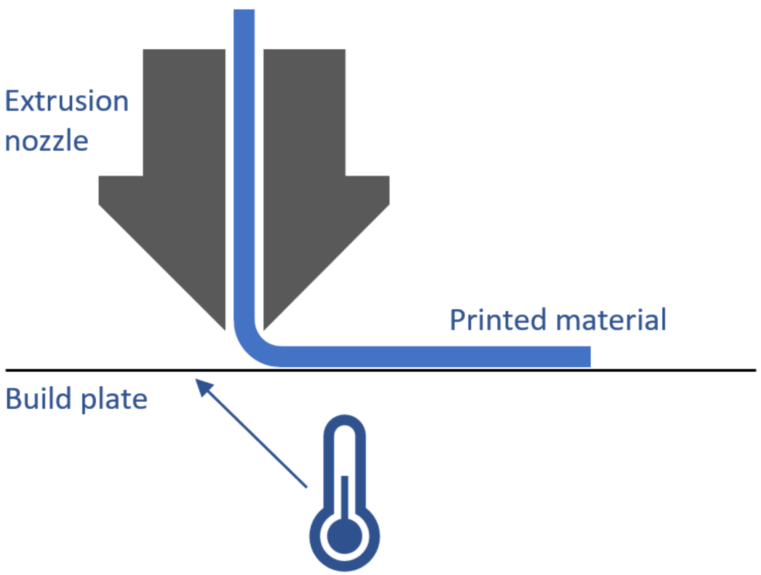
Testing

50% and 100% fan speed

MANUFACTURING

BUILD-PLATE TEMPERATURE

Build-plate temperature refers to the temperature of the print bed on which the object is printed. Depending on the specific printer, the print bed can be heated for better adhesion of the object to the build-plate.

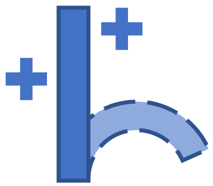


Schematic overview of the FDM printing process, indicating the most important components involved. The component related to the build-plate temperature parameter (build plate) is pointed out in the figure.

SELF-DEFORMATION

A higher build-plate temperature leads to decreased self-deformation. With a cooler build plate, the material cools faster, causing more internal stresses to be retained in the material. By increasing the build plate temperature, the material cools slower, allowing it to already lose some internal stresses. As build plate temperature mainly influences the bottom layer, the influence of this parameter is greater in thinner objects.

SHAPE RECOVERY



Based on the effect on self-deformation, it is expected a higher build-plate temperature increases shape recovery. However, this has not been documented, so the extent to which build plate temperature affects shape recovery is unknown. Furthermore, as mentioned under self-deformation, the extent to which this parameter has an influence on the printed object depends on the size (thickness) of the object.

ACTIVATION TIME

Unknown

Literature

Kačergis et al. (2019): 25, 40 and 60°C build plate temperature

Testing

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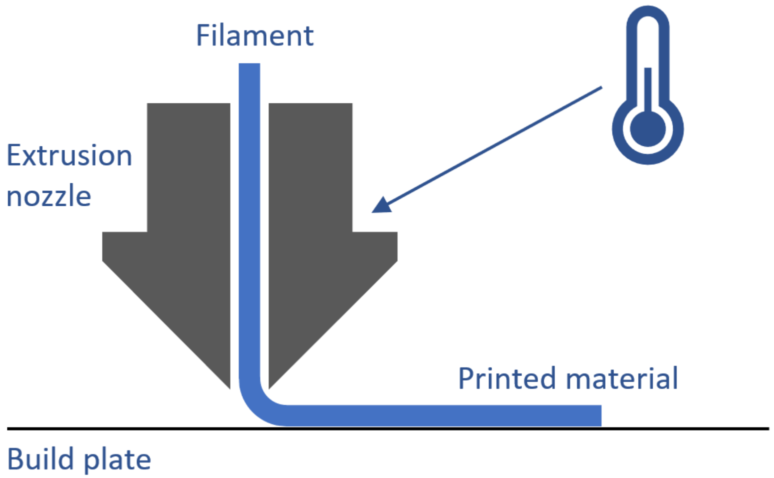
MANUFACTURING

NOZZLE TEMPERATURE

Nozzle or printing temperature refers to the temperature of the nozzle through which the material is extruded. Since different materials have different thermal properties, nozzle temperature can be changed depending on the specific material used, to ensure proper extrusion.

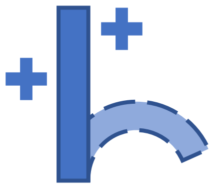


Schematic overview of the FDM printing process, indicating the most important components involved. The component related to the nozzle temperature parameter (extrusion nozzle) is pointed out in the figure.

SELF-DEFORMATION

Increasing nozzle temperature reduces self-deformation. If the material is printed at a higher temperature, the viscosity is lower, allowing for better flow. This, combined with the fact that material printed at a higher temperature needs a longer time to cool down, leads to less internal stresses, thus less self-deformation.

SHAPE RECOVERY



Increasing the nozzle temperature improves the shape recovery of a printed object. Since the presence of internal stresses (self-deformation) is limited with increased printing temperatures, the printed object will return to its printed configuration after deformation.

ACTIVATION TIME

Increasing the nozzle temperature leads to a slight increase in the activation time. However, the effect of this parameter on activation time is small.

Literature

Mehrpouya et al. (2020): 175, 200 and 225°C nozzle temperature

van Manen et al. (2017): 195, 210, 225 and 240°C nozzle temperature

Testing

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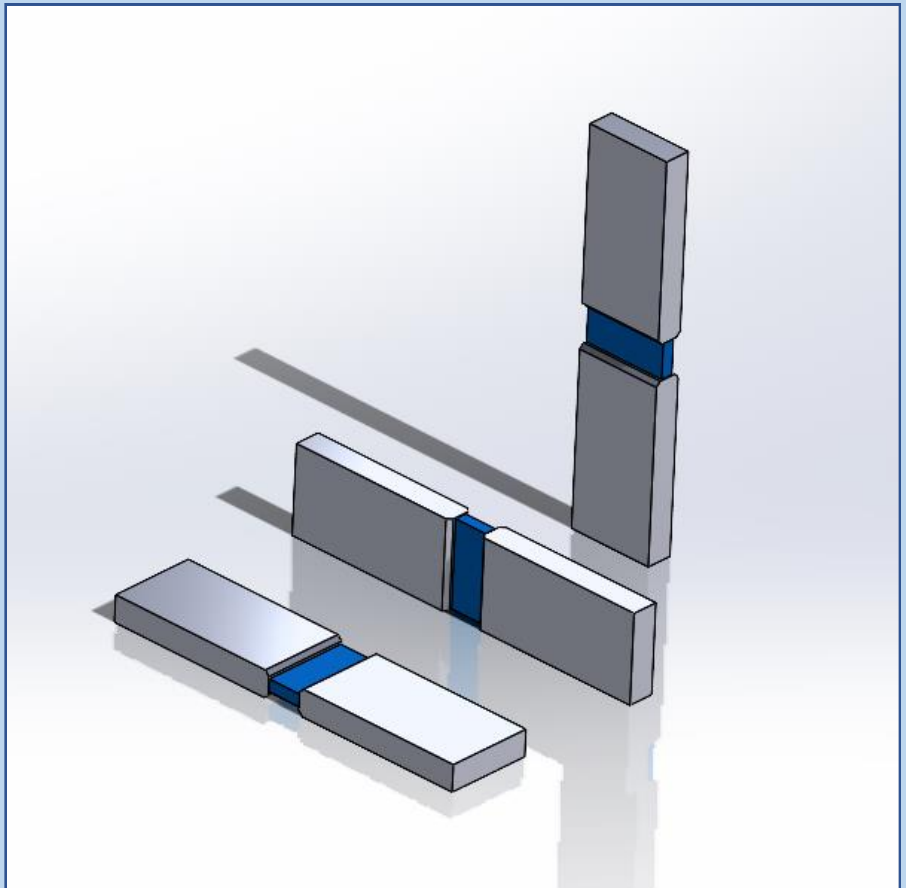
PRINT ORIENTATION

Print orientation refers to the orientation in which an object is printed. While setting up a print, the orientation in which the object will be printed can be specified, in order to achieve better or faster results. Important to keep in mind when specifying the print orientation, is that for certain orientations sufficient cooling is needed to achieve proper surface/print quality.



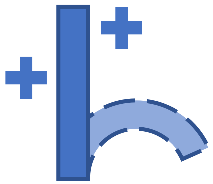
Three examples of printing orientations for a simple shape memory object.

SELF-DEFORMATION

✓

Self-deformation is affected by the orientation the object is printed in, with the extent to which self-deformation occurs being dependent on the specific orientation. Since self-deformation normally occurs as bending upwards from the horizontal plane, self-deformation can be reduced by orienting a print in such a way that the print is largest in the Z-direction.

SHAPE RECOVERY



✓

Shape recovery is affected by the orientation the object is printed in, with the extent to which this affects shape recovery being dependent on the specific orientation. Shape recovery is linked to self-deformation, meaning that the orientation leading to increased self-deformation, will generally decrease shape recovery, while an orientation that limits self-deformation will generally lead to better shape recovery.

ACTIVATION TIME

✓

Activation time is affected by the orientation the object is printed in, with the extent to which this affects activation time being dependent on the specific orientation. What can be said about the effect on activation time is that print orientation affects the number of layers that needs to be printed, and also the orientation of these layers in the active parts. This leads to differences in heat conduction in the active part, which affects activation time.

Literature

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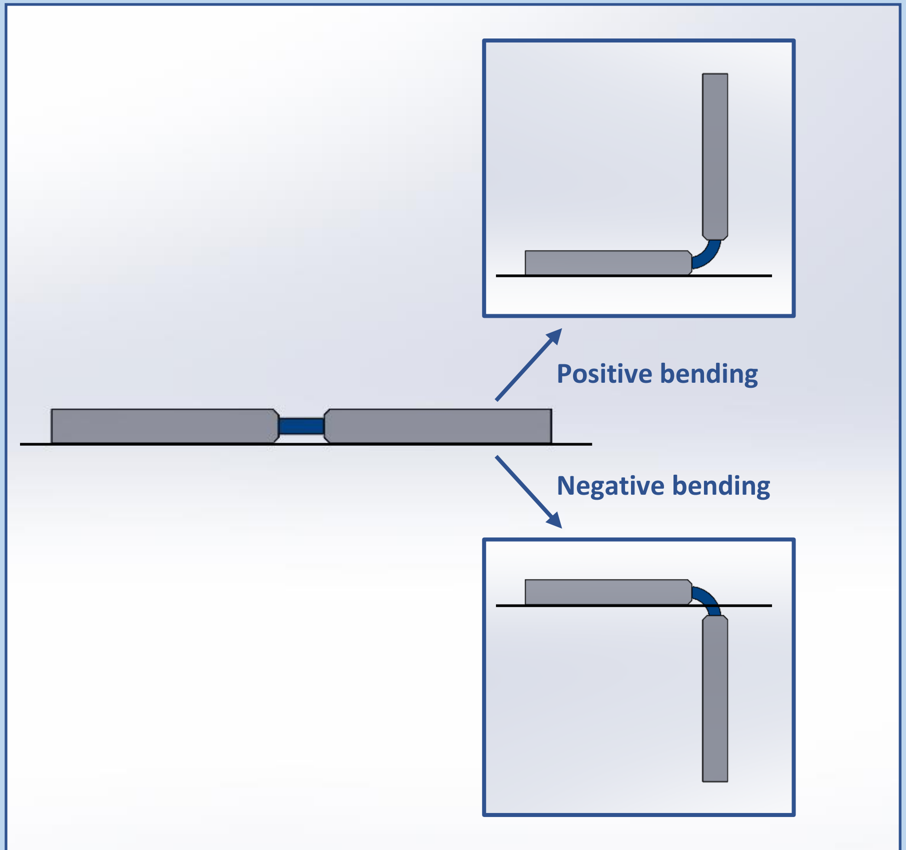
Testing

flat samples printed in different orientations

USE

BENDING DIRECTION

Bending direction refers to the way an active part is deformed in relation to the self-deformation direction. If internal stresses are present in a printed object, self-deformation occurs. Here, we refer to positive and negative bending directions, which mean bending in the same direction as the self-deformation and in the opposite direction of self-deformation respectively.



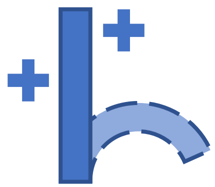
Side view of a simple object with an active hinge part (blue) being bended in positive and negative direction. With the black line under each object resembling the build plate.

SELF-DEFORMATION

✗

Bending direction has no effect on self-deformation.

SHAPE RECOVERY



✓

Shape recovery can be greatly affected by bending direction, dependent on the amount of internal stresses, thus, self-deformation, being present in the printed object. A high degree of self-deformation means decreased shape recovery, while a low degree of self-deformation means improved shape recovery, since the material wants to return to the state with no internal stresses. However, when comparing recovery for samples with a high rate of self-deformation to samples with a low rate of self-deformation, when combining negatively and positively bended results, the average always is around 96-97%. Utilizing this parameter in the right way can lead to 100% shape recovery. For this, the active part should have some internal stresses and be bended negatively.

ACTIVATION TIME

✓

Bending direction has no significant effect on activation time. However, in testing, it was observed there are differences in activation time between negatively and positively bended samples, with the negatively bended samples having longer activation times.

Literature

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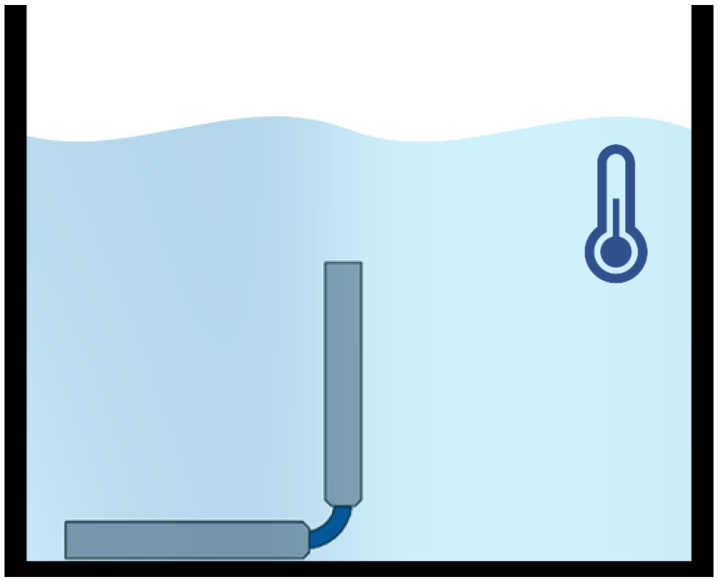
Testing

flat samples bended 90 degrees in either positive or negative direction

USE

ACTIVATION TEMPERATURE

Activation temperature refers to the temperature of the activation medium in which the shape memory material is activated. This is not the same as the temperature at which a material activates. While thermally activated materials need to be heated above their glass transition temperature to activate, the environmental/activation temperature with which this is achieved can vary.



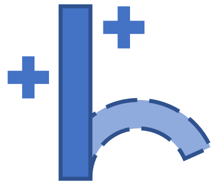
Schematic side view of a simple, deformed sample emerged in hot water to initiate shape recovery. The activation temperature in this illustration refers to the temperature of the water, since this is the activation medium.

SELF-DEFORMATION

⇧

Activation temperatures which are further above the glass transition temperature lead to more self-deformation. Higher temperatures allow the internal structures to move more freely, enabling the material to reach the state of highest entropy more easily.

SHAPE RECOVERY



⇧

Activation temperatures which are further above the glass transition temperature lead to improved shape recovery. Higher temperatures allow the internal structures to move more freely, enabling the material to reach the state of highest entropy more easily. However, if the object will in fact recover better to its printed shape depends on the internal stresses present in the material after printing, since an increased activation temperature also leads to more self-deformation. Therefore, internal stresses need to be limited as much as possible for activation temperature to cause better shape recovery.

ACTIVATION TIME

⇩

Activation temperature has a small effect on the activation time, with higher activation temperatures leading to slightly lower activation times. Activation temperature has little effect on the initial heat penetration, therefore the effect on activation time is small.

Literature

Mehrpouya et al. (2020): 65 - 75°C activation temperature (water)

van Manen et al. (2017): 65 - 95 °C activation temperature

Testing

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LITERATURE

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