Case study for quality control & quality assurance in metal additive manufacturing: A dental bridge

Keywords: Dental bridge, quality in dentistry

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Introduction

On the ManSYS website, quality in metal AM is discussing according to the AM value chain. Quality issues discussed in this value chain are relevant for metal AM in general and the value chain can be used for different applications. In this chapter, we use of the AM value chain in an application driven manner, for the fabrication of a dental bridge.

The structure of this chapter is similar to the AM value chain (depicted below). First, requirements for the dental bridge are defined. Following on the requirements, the AM workflow, including design, material, process and post-processing, is described and quality aspects are discussed. Furthermore, quality in the additive manufacturing process of a dental bridge is extrapolated to the additive manufacturing process of other dental prosthetics, including crowns and frameworks.
**Product description**

A dental bridge is a fixed dental restoration which is used to replace a missing tooth. The bridge itself is a series of artificial teeth, which can be placed on adjacent teeth (Figure 1). In case the patient has few teeth left, the bridge can be cemented on abutments. Abutments are support structures which are placed on implants to be used as foundation for dental prosthesis (i.e. crowns, bridges, frameworks).

The dental bridge has to match the support teeth or abutment perfectly. It will be cemented on the supports and extra fundamental attentions will be provided, to optimize the fitting and match the surface roughness of the natural teeth.

A dental bridge is the replacement of a tooth, and is therefore a dental prosthesis. Other dental prosthetics are crowns and frameworks. Crowns are single tooth replacements, placed on either an abutment or a remaining tooth cap. Frameworks are substructures which are used as support for partial dentures. Many quality aspects for the manufacturing process of a dental bridge, also account for other dental prosthetics.

![Figure 1](image1.png) **Figure 1** Representation of a dental bridge and its fitting.
Product requirements
Requirements for a dental bridge are the following:

- The aesthetics should be similar to the natural teeth of the patient
  - In terms of shape
  - In terms of colouring
- Mastication of a patient should remain comfortable
- Phonation of a patient should remain comfortable

These requirements account for all dental prosthetics: crowns, bridges, frameworks, inlays, dentures and more (NVQ for Nurses, 2009). To meet these requirements, the following quality aspects need to be assessed during the manufacturing process. These quality aspects can be referred to as the process window.

- Mechanical behaviour
- Thermal condition of “firing” the ceramic powder to obtain the right colour
- Right design (CAD or handmade)

The material need the required biocompatibility and properties. For titanium and cobalt chrome, the certifications listed in table 1 are required.

<table>
<thead>
<tr>
<th>Certifications</th>
<th>Summary of description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 22674:2006</td>
<td>Classifies metallic materials that are suitable for the fabrication of dental appliances and restorations</td>
</tr>
<tr>
<td>ISO 9693-1</td>
<td>Specifies test methods for determining the compatibility of metallic and ceramic materials used for dental restorations by testing the composite structure.</td>
</tr>
<tr>
<td>ASTM F2924</td>
<td>AM specific standard for Ti6Al4V alloys</td>
</tr>
<tr>
<td>ASTM F1472</td>
<td>The use of Ti6Al4V alloys for surgical implant applications</td>
</tr>
<tr>
<td>ISO 5832-3:1996</td>
<td>The use of Ti6Al4V alloys for surgical implant applications</td>
</tr>
<tr>
<td>ASTM F136</td>
<td>The use of Ti6Al4V alloys for surgical implant applications</td>
</tr>
</tbody>
</table>

| Table 1 Certifications for metals used in the SLM process |

- Accuracy

The shape of the bridge needs to be perfect for aesthetic reasons and for the fitting of the prosthesis. Accuracy is determined in the design and manufacturing process of the prosthesis. An accuracy of 20 µm is sufficient for every dental application, including intra orally used prosthetics. However, many dental applications can be manufactured with a much lower accuracy.

- Ceramic coating

The ceramic coating of AM processed bridges need the required surface quality and aesthetics.

- Production costs should be low
Traditional production methods, using waxing and investment casting, obtain the required quality of a dental bridge and dental prosthetics. Therefore, costs of an AM manufactured part, need be lowered compared to traditional production methods.
Design
For design of the dental bridge, we use the structure, as presented in the AM value chain, considering of four main steps and several sub-steps:

- Original part
  - Definition of geometry (CAD)
  - Definition of load cases and constraints
  - Part requirements
  - Analysis of original component
- Topology optimisation
  - Optimisation parameters
  - Assessment of results
  - Assessment of mesh sensitivity study
- Part re-design
  - Materialise 3-Matic software
  - Regularise, smooth, and replace unwanted aspects
  - Re-mesh
  - Add substructures
- Final verification
  - Re-mesh
  - Analyse under design loads
  - Verify adequacy of solution

Quality in part design
Several quality issues play a role in the design of a dental part. Design issues can be challenged with design software. Parameters in the software settings filter for multiple design failures. Parameters in this software can be set to obtain the right design (both internal as wall thickness or cement material required for the finishing of a restauration, or external as typology of cusps or roundness od the tooth). Furthermore, the specific outline of a product (essential for the coupling between an abutment and the bridge) can be indicated. Milling these precise outlines can be extra precise, ensuring the accuracy and fitting of the product.

The most important aspect in design comprises the fitting of a prosthesis. The dental technician designing the prosthesis is responsible for the fitting and design. Software parameters can determine the shape of a bridge for (as an indication) 80%. The remaining design is in the hands of a dental technician. Although the technicians influence may be merely 20%, there is a difference in quality in the design of a skilled dental technician compared to a less skilled dental technician.

For topology optimization, lightweight structures can improve quality of a prosthesis. Complex dental frameworks at the lower mandibular jaw can be heavy, which is not comfortable for a patient. A lightweight structure is in that case preferred. On other applications, like crowns and bridges, weight is not an issue and therefore topology is of limited added value.
Original part

The dental bridge provided by Wisildent consisted five Khono cannula’s. The Khono cannula’s is an abutment, which can be placed upon a Khono implant. We can identify the Khono cannula’s on the dental bridge easily (Figure 2).

![Figure 2 STL geometry of the dental bridge with five Khono cannula’s. The left image shows native surface triangulation, the right image shows a smoothed image without mesh.](image)

The main issues affecting the design optimisation of the Wisildent part was that there was no CAD file equivalent of the STL file available. Abaqus/CAE has the capability to import STL files; however, the imported “orphan mesh” does not contain any geometric features (i.e. vertex/edge/face/volume information). In Abaqus/CAE there are tools where the analyst can create faces from orphan mesh element faces. However, this can only be applied to one face or a small group of faces at a time. As the STL file under consideration had over 150,000 surface elements, this approach was not feasible. Alternatively, Abaqus/CAE has the option to convert a surface triangulation to a volumetric mesh of tetrahedral elements. However, the triangulations that are typically found in STL files are not suitable for finite element mesh generation as they contain very high aspect ratios or small internal angles. In any event, the resulting volumetric mesh of tetrahedral elements, even if it would be acceptable from a finite element analysis point of view, would still be an “orphan mesh” without any geometric features. Consequently, no mesh refinement could be performed and therefore limited additional work could be performed on the three-dimensional mesh.

Therefore, in order to carry on with the Wisildent part optimisation, an idealised CAD model of the as-provided geometry was created. This idealised part contained all of the same features and dimensions of the original part, but was regularised with standard geometric shapes (ellipses, chamfers, etc.). The idealised part is shown in Figure 3. The idealised part is suitable to demonstrate the capabilities of design optimisation on a part typically manufactured by the dental industry. Although topology optimisation is typically applied for mass production as opposed to mass customisation, the principles of design optimisation arising from this study of an idealised part could then be applied to bespoke, customised parts.
**Figure 3** Original dental bar from Wisildent (left) versus the idealised geometry created for analysis (right).

**Finite element mesh**

The idealised part was meshed entirely with quadratic tetrahedral elements with a global seed size of 0.5mm.

**Loads and boundary conditions**

A study by Zhao and Ye (1994) assessed the biting force of humans and found that maximal value was approximately 265lb force or 2MPa biting pressure. In the finite element model, this biting pressure was applied to the top of all annular surfaces representing teeth. The applied load was resisted by boundary conditions which were created in a way to simulate cantilever-type bending. Figure 4 illustrates the loads and boundary conditions.

**Figure 4** Loads and boundary conditions for the dental bar (left) and typical, cantilever-type bending deformation resulting from the applied loads and boundary conditions.
**Topology optimisation**
The objective of the topology optimisation of the Wisildent part was to reduce weight and maintain stiffness. To do so, the part was partitioned into frozen and unfrozen regions as shown in Figure 5. First, for each tooth, the entire region around the tooth was frozen (tan regions in Figure 5). The regions between the teeth were “skinned” with a 0.5 mm thick layer of frozen material (red regions in Figure 5). The interior volume of the regions between the tan regions were classed as unfrozen where material could redistribute (blue regions in Figure 5). Small holes were extruded into the bottom of the part based upon the experienced gained from the topology optimisation of the intramedullary nail. These holes would allow loose powder to exit any substructure generated in the blue regions during manufacture.

![Figure 5 Frozen (tan and red) regions and unfrozen interior regions (blue).](image)

The volume properties of the part are shown in Table 1.

**Table 1 Volume properties of the dental bar.**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Total volume of idealised part</td>
<td>1417.02mm³</td>
</tr>
<tr>
<td>Total volume of frozen regions</td>
<td>1103.12mm³</td>
</tr>
<tr>
<td>Total volume of unfrozen regions</td>
<td>313.90mm³</td>
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</tbody>
</table>

The specific parameters of the topology optimisation are shown in Table 2.

**Table 2 Definition of the topology optimisation parameters for topology optimisation II.**

<table>
<thead>
<tr>
<th>Domain of definition for strain energy</th>
<th>Entire part</th>
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</thead>
<tbody>
<tr>
<td>Domain of definition for control volume</td>
<td>Unfrozen red and tan region from Figure 28</td>
</tr>
</tbody>
</table>
Optimisation algorithm | General, sensitivity-based
---|---
Target volume reduction | 30% of original volume of unfrozen region
Frozen regions | Blue regions from Figure 28
Stopping criterion | None. Limited to 25 iterations.
Minimum member size | 0.5mm

**Results of topology optimization**
All of the volumes designated as “unfrozen” essentially disappear; that is, the topology optimisation indicates that the material in the unfrozen regions can be removed. This is illustrated in Figure 6 where the normalised material density is shown. In this figure, blue regions correspond to zero material density (i.e. the recommendation that no material is present), and red regions correspond to regions of full material density. The figure has been generated by cutting the full model along different planes to show the interior volume. Only two slices are shown, but the results indicate that the entire frozen region can be eliminated.

![Figure 6](image_url)

**Figure 6** Normalised density of the Wisildent demonstrator after optimisation.

From the volume properties given in Table 2, the unfrozen regions represent about 22% of the total volume of the part. The resulting stress analysis on the optimised part indicates that the stresses are actually slightly lower in the optimised part. This means that it is feasible to potentially reduce the
weight by 22% if the unfrozen regions are completed removed (and large interior voids are present in the final part). Alternatively, if more information becomes available about the load requirements of the part, then additional stiffness could be obtained by replacing the interior voids with low-density micro-scale substructures or lattices. Suitable outlet holes have already been incorporated into the geometry to allow for any loose powder arising from the internal structures to be flushed out.

The only problem connected with this topology optimisation is the strong modification of the external shape. The bottom part of the dental bar should be created on the shape of the gum. In fact the bar has the same shape of the gum with a distance offset form it.

More work is needed to obtain the same topology optimisation characteristics without modifying the external shape.

**Part redesign**
Support structure with Materialise Magics have been constructed and are shown in figure 7.

![Figure 7 SLM orientation and supports](image_url)
Material

Material requirements
The material requirements for cobalt chrome in metal AM are described in chapter ‘Materials’. Material quality aspects for dental applications are i.e. biocompatibility, surface roughness, tensile strength and layer thickness. The ISO applicable certifications for cobalt chrome, ISO 9693-1 and ISO 22674:2004, ensure the used material has the required material properties.

The most quality aspects of a product are determined by the choice of material. Such aspects can be material hardness, monolithic properties or porosity. Hardness of material influences the stability of a prosthesis, but on the other hand, hardness influenced the comfort of wearing. Monolithic properties influence the colouring and require post processing. Aesthetic properties of a dental prosthesis are influenced. The porosity of a material effects the uptake of food scraps and bacteria’s which are in the mouth.
## Machine & process parameters

The following machine and process parameters are used for CoCr 15-45 μm SLM at 30μm layer thickness:

Heater Setting: 150°C

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<th>Parameter</th>
<th>Exposure (μs)</th>
<th>Point Distance (μm)</th>
<th>Laser Power (mA)</th>
<th>Laser Frequency (Hz)</th>
<th>Lens Position (mm/100)</th>
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</tbody>
</table>
Post-processing
In order to obtain a final part it is necessary to develop these steps:

- Remove part from the build platform
- Remove supports
- Sandblasting the surface
- Clean the part to ensure that there is not dust
- Machine the holes and the surfaces to fit with other parts.
Maintenance & metrology

Metrology:

- Check the scanned file and design by designer
- Manual checking dimensions by using a model
- Visual colour check against colour standard.
- Visual inspection by operator

Maintenance of the dental bridge requires regular check-ups with a dentist to inspect the quality of the prosthesis.