Manufacturing of the Oloid. CAD/CAM Workflow

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Abstract. This paper considers the manufacturing process of the Oloid by means of numerical control machining. Firstly, the requirements of the end part were studied, and it was decided to manufacture the Oloid via gravity die casting, and its necessary mold to be produced by CNC machining. In order to do so, the gating system and mold had to be designed and tested using sand casting methods. When the test results were optimal the die was machined and the part cast. During this process the CAD/CAM workflow was object of observation and study, which allowed for insight and conclusions on the design process.

1. Introduction
Therefore, this paper takes the manufacturing of the Oloid as a target and explores how to do so, using CNC machining and die casting to achieve it. We can identify three main goals in the project.

- The manufacturing of the Oloid. A mathematical sculpture with technical and mechanical value to it. This way extending Paul Schatz’s work from a mechanical engineering and an artistic point of view.
- The full understanding of the CAD/CAM workflow. From the design phase to the production.
- The development of a die for this geometry.

2. The Oloid
Paul Schatz discovers the Oloid in 1929, because of his research in cuboid solids.

2.1. Geometry
It is the convex hull of the frame created by placing two circles of radius R perpendicular to one another, making the center of each circle coincide with the edge of the other (Figure 1, Figure 2) [1].

![Figure 1. Oloid.](image1)

![Figure 2. Oloid construction.](image2)

![Figure 3. Developed surface.](image3)
• On a slightly inclined level, an Oloid starts to roll very quickly. It has an energy efficient movement.
• All its surface (developable) touches the ground at some point when rolling (Figure 3).

2.2. Kinetics
This body has a characteristic tumbling motion (from which it also derives): inversion. A third type of movement, different to translation and rotation. A rhythmically pulsating 8-shaped movement, comparable to the movement of a double lemniscate, set at 90º angle one from the other.

2.3. Field of use
The specific inversion movement makes this piece an asset in three main areas.
• In water treatment and purification. By submerging the Oloid below the surface of the water and making it move, a very energy efficient stirrer is achieved.
• As a propulsion system. For this, it must be mounted with two perpendicular axes.
• As a mixer. Using the double lemniscate movement.
• Work of art. Because of the intrinsic artistic value this geometry encloses.

3. Manufacturing of the part
The part is then studied in order to determine what manufacturing method and parameters suit best. Depending on the available resources, funds and time, initial conditions change as the project evolves.

3.1. Part and geometric requirements
The end piece must ensure the following.
• Precise dimensions
• Good superficial finish
• Accurate geometry
• Minimum post-processing
• Adequate volume for machining and for comfortable and ergonomic handling of the part.

The lack of flat surfaces to grip the part make it difficult to be CNC machined, therefore the part is manufactured by gravity die casting, and the die CNC machined. Observing the geometry in Figure 2, there are some aspects to take into consideration.
• The body is symmetrical in two perpendicular planes.
• Its lack of a flat surface makes it impossible to grip with a machine.
• The Oloid is a thick volume. Keeping the volume smaller will diminish possible hotspots.
• The sharp edges. For these edges to exist, an interior sharp ridge in the mold must be made, which is impossible to produce in CNC machining. The solution chosen for this is to allow an inner radius, since the sharpness of the edges is not a priority to the project as the shape will not be used for mechanical purposes, and other options entail additional costs.

3.2. Manufacturing

3.2.1. Gravity die casting. All in all, this manufacturing method is adequate when comparing with the requirements stated previously for the part. Some of the advantages of this process are:
• Better surface finish and dimensional tolerances than sand casting.
• High strength, toughness and ductility. Fine grain structure because of the higher cooling rate.
• The main disadvantage is the high cost of the die.

The biggest issues in terms of quality that should be minimized with a well thought out design are:
• Turbulence, oxide, solidification shrinkage and micro-shrinkage porosity.
3.2.2. Machining. CNC milling is an adequate process for the manufacturing of the mold since it’s a flexible machining method that allows to create a wide range of geometries. For now, the existing restrictions of this process that affect the initial mold design are:

- Minimum available tool diameter: 1.5 mm.
- Grip: the clamping system holds 8 mm depth of the part.
- Machine type: 3 axes machine.

3.3. Materials

There are two different materials to be selected, shown in Table 1.

- Mold. The chosen mold material is AW 2007, AlCuMnPb F37. The thermal and mechanical loads that this process entails [2], are minimized in this case because it is not a pressure casting operation and the production volume is low, which allows the use aluminium instead of the usual iron.
- Part. the alloy selected for this project is tin based. It is easily obtained and economical. However, the surface finish it allows is not as optimal as other options. Most importantly its low melting point makes it compatible with the die material, AW 2007, creating less thermal strain upon the mold. Also, tin is known for its fluidity, formability and dimensional stability, with low solidification shrinkage.

| Components (%) | Density (kg/dm³) | Melting point (ºC) | Specific heat (J/Kg) | Tensile strength (N/mm²) | Brinell hardness | E (Mpa) | Shear mod. (Mpa) |
|----------------|------------------|--------------------|---------------------|-------------------------|------------------|---------|-----------------|
| Cu4.3/Mg 1.1/Pb | AW 2007          | 2.85               | 507-650             | 860                     | 370-470          | 100-140 | 73000           |
| 24Sn, 76Pb     | SN 32            | 9.26               | 190-260             | -                       | 50               | 15      | -               |

4. Iteration 1

4.1. Design and dimensioning

4.1.1. Dimensioning of the Oloid. With the above limitations the chosen dimension for the Oloid is R = 25 mm. We avoid working with an overly large solid piece for casting, also, its size is not too small to handle when milling the mold. Being the total length of 75 mm. The radii for the interior edges is set at 1 mm (limited by tool size), which is visually insignificant.

4.1.2. Design and dimensioning of the mold. The main issues to be avoided through the design of the mold are premature solidification in the gating system (thin sections), hotspots and a different cooling rate, with a potential formation of shrink cavities in the cavity. Also, in order to avoid gas entrapment, the Oloid shape stands vertical in the mold, and in the centre top of it, an air escape channel is placed, creating a “chimney effect”. After some proposals, the chosen distribution for an initial design is as shown in Figure 4. This distribution has a bottom feeding system that prevents turbulence [3].

The chosen gating system is a non-pressurized system of As:Ar:Ag, 1:1:1, which maximizes flow velocity in the gate and minimizes its solidification and blockage of material flow. Pouring basin and sprue. The pouring basin and sprue have been merged into one. The lower section of the sprue is the choke (non-pressurized system), and the higher section is also the pouring basin. The sprue is curved and connects straight to the runner (inner radius = runner width), guaranteeing a smooth and gradual change in flow of the molten metal. The sprue has a 15º taper [4].
Table 2. Dimensions of Oloid.

| Radius (mm) | Shrinkage (%) [4] | Overdim. radius (mm) | c (mm) - height body |
|-------------|--------------------|----------------------|---------------------|
| 25.00       | 0.60               | 25.15                | 75.45               |

Table 3. Weight of part and gating system.

| ρ (kg/m³) | Vol (mm³) | W(Kg) | Wgat-sys (Kg) | Wtot (Kg) |
|-----------|-----------|-------|---------------|-----------|
| 9260.00   | 48557.69  | 0.45  | 0.44          | 0.89      |

Table 4. Gating system and part heights.

| h2 (mm) - height of sprue | c (mm) - height of body | h (mm) - effective height¹ |
|---------------------------|------------------------|-----------------------------|
| 75.00                     | 75.45                  | 37.28                       |

¹Effective sprue height calculated with equation (1).

\[ h = h2 - c/2 \]  

Area of the choke is now calculated with equation (2) [5].

\[ A_{S2} = Ac = l x c = W(\mu g t (2gh)^{1/2})^{1} \]  

- μ = efficiency factor
- g = acceleration due to gravity
- t = pouring time = 4 s. Estimated from a trial casting process in laboratory of HTW Berlin.

Runner. Made slightly longer to avoid turbulence. Its section is as in equation (3).

\[ Ar = Ac \]  

Gates. After research, a minimum thickness of 2mm is decided, to avoid post-processing [5]. This is a critical point to keep under observation once the mold has been made and put to work. Section as in equation (4).

\[ Ag = Ac \]  

Table 5. Final calculated dimensions. Iteration 1.

| \(A_{S2} = Ac_2\) (mm²) | \(A_{S1}\) (mm²) | \(Ar\) (mm²) | \(Ag\) (mm²) |
|--------------------------|------------------|-------------|-------------|
| 50.93                    | 1828.10          | 50.93       | 50.93       |
| DS₂ (mm)                 | DS₁ (mm)         | Dr (mm)     | I₁ (mm) x I₂ (mm) |
| 8.10                     | 48.25            | 8.10        | 2.00 x 25.47 |

All sections have been designed with a circular profile, corners rounded, and lines slanted, to facilitate extraction of part. The dimensions can be seen in Table 2, Table 3, Table 4 and Table 5.

Figure 4. Iteration 1.  
Figure 5. Result 1.  
Figure 6. Result 2.
4.2. Testing and redesign

As CNC milling is not a cost-effective process, the testing is done with a sand casting process. However, we must keep in mind the differences between both processes when analyzing the results. The part and gating system is 3D printed in two halves that are used to create the sand cast, and then this cast is tested, first with Wood’s metal (Figure 5), and when this is successful with Tin alloy, the material of the final part (Figure 6).

4.2.1. Analysis of results and conclusions

Observing both resulting parts in Figure 5 and Figure 6, there are finishing imperfections like porosity or roughness due to the sand casting process.

- The edge interior radii, the curvature and finish of this seem optimal in both parts.
- The 2 mm wide gate has successfully filled the cavity premature solidification.
- In result 2, there is a large pore located near the air escape section.

4.2.2. Redesign based on analysis

The previous observations are implemented into a new design.

- Transformation of air escape vent into riser. The volume must be enlarged to provide enough metal.
- With the new riser, the sprue can be reduced in taper and a pouring basin is incorporated.

A new riser is calculated following both the Volume method and Chorinov’s rule [6]. However, in order to design a riser that does not enlarge the height of the gating system, this one only compensates about half the calculated volume and doesn’t follow Chorinov’s rule. Nevertheless, because of the successful casting process in Iteration 1, it is considered that this riser should be sufficient.

5. Iteration 2

5.1. Design and dimensioning of the mold

All calculations are done in the same manner as Iteration 1, except:

- Pouring basin. h1 = 20 mm and width of db1 = 40 mm.
- Sprue. Once again, the sprue is tapered, calculated with equation (5) [5]:
  \[ \frac{A_{S2}}{A_{S1}} = \left( \frac{h_2}{h_1} \right)^{1/2} \]  
- t = 3 s instead of the 4 s previously decided.
- Riser. With a cross section connecting to the cavity of same size and shape as the gate.

The resulting calculations can be viewed in Table 6 and the design in Figure 7.

| Ab1 (mm²) | As2 = Ac (mm²) | Ab2 = As1 (mm²) | Ar (mm²) | Ag (mm²) |
|-----------|----------------|-----------------|-----------|-----------|
| 1256.64   | 44.00          | 85.21           | 44.00     | 44.00     |

| Db1 (mm) | Ds2 (mm) | Ds1 (mm) | Dr (mm) | l1 (mm) x l2 (mm) |
|-----------|----------|----------|---------|-------------------|
| 40.00     | 7.50     | 10.40    | 7.50    | 2.00 x 22.00      |

Table 6. Final calculated dimensions. Iteration 2.
5.2. Testing and redesign
Once again, the part is tested in Wood’s metal (Figure 8). The results show no considerable errors, only those related to the sand casting process. Therefore, this redesign is proven successful and an improvement to Iteration 1 because of the smaller amount of material usage and the lack of pores.

6. CAD
The actual die is now dimensioned and modelled in CAD with two positioning pins (8 H7 and 10 H7) that with a clamping system hold the mold together.

- The size of the preform is: 100 mm x 100 mm x 40 mm.

7. CAM
The modelled CAD geometry is now processed by CAM (Computer Aided Manufacturing), in order to program the manufacturing process, toolpaths and control the CNC machine. The CAM software used in HTW CNC machines is HyperMill, by OpenMind. Some of the steps in the process are the following.

7.1. Joblist and tool dimensioning
A rough outline of the process follows. With the clamping system in the position for Subphase 1 (Figure 9), the top surface is face milled (Roughing and Finishing) using the largest 45° cutting mill possible. Then the sides of the part are milled (30 mm deep) using a long enough 90° tool, which is then used to empty rapidly the Oloid cavity (roughing). This same cavity is then further emptied with a ball mill (roughing), followed by one of a smaller radius (roughing) with which the finishing pass will also be done. These two last steps are then repeated for the other cavities. After all the large geometry is done, the small radii and gaps are milled with the smallest cutter, 1.5 mm diameter. The holes for the locating pins are then drilled.

The second clamping position is now activated, Subphase 2, and the bottom side of the mold is now milled, with roughing (8.5 mm) and finishing (0.5 mm).

To choose the precise tool dimensions, two main factors are:
Available tools in laboratory (those relevant to this project).
- 63 mm diameter head with 45° cutting inserts for face milling.
- 16 mm diameter 90° tool.
- Ball mills with 2 cutting edges of diameters: 1.5, 2, 4, 8, 10, 16 (mm).

Limiting geometry:
- In basin, sprue and runner the minimum section has 7.4 mm diameter.
- In gate and gate to riser the minimum section has 2 mm width.
- Interior radii in Oloid cavity are 1 mm.
Mills of several radii are used, starting with a larger one to remove material quicker, and continuing with smaller ones. Several options are simulated in CAM and the least time consuming is chosen.

7.2. Tool and operation parameters
After the initial outline of the tools and operations, the tool manufacturer’s handbook is used to determine the recommended parameters for each tool in every type of operation in which it is used.

7.3. Implementation in CAM. PPR
All the data is then introduced in HyperMill, one operation at a time, choosing a series of parameters.

7.3.1. Each job in the joblist is defined. The creation of the joblist follows the operations previously stated. The final joblist can be viewed in Table 7. The setup is as follows:
- Different parameters for the operation are introduced.
- The toolpath is calculated and validated.
- Statistics, being time the most important, are calculated and taken into consideration.
- The job is simulated with “internal machine simulation”.

Time, toolpaths and simulations of the different settings are compared to choose the best ones for every operation and the optimal toolpath, horizontal and vertical stepovers are determined. It is only during the actual set up of each operation that we can fully know if the planned sequence is correct, for this reason some changes are made to the initial outline of the joblist. The most notable ones:
- General operations of roughing and then finishing for the cavity + gating system are carried out.
- After this, each area is specifically machined with “Directional cavity contouring”.
- The smaller diameter tools and the more intricate geometry cause the tool holder to collision against the part. Because of this, 4 other coordinate systems must be defined for different areas for the tools to approach the part from a different angle and not interfere with it, image available in Figure 10.
- A recontouring operation for the gate between the Oloid cavity and the riser has to be done after observing remaining material in the simulation.
- Also, because the simulation doesn’t show completely accurately the finish after every operation due to its resolution, these operations are grouped, not by area, but by type of operation. This way, it is possible to stop the process when machining, if viewed that the surface achieved by roughing with D1.5 is optimal enough, allowing to reduce machining time and costs considerably. This also helps to reduce the number of tool changes.

The operations that have just been described comprise a closed CAM program for the part (CAM 0). Nevertheless, it is not the final CAM, because as we will see later, after the test manufacturing some changes are made to it, creating CAM 1 and then CAM 2.

7.4. Simulation and analysis
- The machining of the whole part has been done in a sequence of 30 operations.
- The time for the whole process is of 9:05:52 (h:min:sec). If in production, after machining with a certain tool the surface finish is considered sufficiently smooth, the part will then not go on to the next phase/tool. For instance, stopping the process after the Contouring D1.5 (roughing) set of operations, leaves the whole process to a short duration of 1:04:33 (h:min:sec).
- In addition, it is important to note that the possibilities of job settings are endless, and we could be leaving out other more optimal toolpaths that could lead to more time efficient processes.
Table 7. Final joblist and tools.

| Nbr. | Operation               | Tool Nbr.         | Tool description          | Nbr. | Operation               | Tool Nbr.         | Tool description          |
|------|-------------------------|-------------------|---------------------------|------|-------------------------|-------------------|---------------------------|
| L1   | Face milling (R.)       | ON6H063R00        | Inserts 45º D63           | L1.6 | Contouring D1.5 (R.)    | A2 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L2   | Face milling (F.)       | ON6H063R00        | Inserts 45º D63           | L1.7 | Contouring D1.5 (F.)    | A3 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L3   | Side milling (R.)       | 40160-HEMI (J40)  | End mill D16              | L1.8 | Contouring D1.5 (R.)    | A4 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L4   | Side milling (F.)       | 40160-HEMI (J40)  | End mill D16              | L1.9 | Contouring D1.5 (F.)    | A1 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L5   | Cavity Empting (R.)     | 40160-HEMI (J40)  | End mill D16              | L1.10| Contouring D1.5 (F.)    | A5 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L6   | Contouring D16 (R.)     | 450160-MEGA-T (JH450) [SECO] | Ball mill D16 | L1.20| Contouring D1.5 (F.)    | A1 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L7   | Contouring D10 (R.)     | JS534100D18 (GZI-MEGA [SECO]) | Ball mill D10 | L1.21| Contouring D1.5 (F.)    | A2 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L8   | Contouring D4 (R.)      | 450040-MEGA-T (JH450) [SECO] | Ball mill D4 | L1.22| Contouring D1.5 (F.)    | A3 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L9   | Contouring D4 (F.)      | 450040-MEGA-T (JH450) [SECO] | Ball mill D4 | L1.23| Contouring D1.5 (F.)    | A4 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L10  | Contouring D2 (R.)      | 416020-MEGA-T (JH416) [SECO] | Ball mill D2 | L1.24| Recontouring D1.5 (F.)  | A5 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |
| L11  | Contouring D2 (R.)      | 416020-MEGA-T (JH416) [SECO] | Ball mill D2 | L1.25| Drilling D7.8           | 11 3150 [Hoffman] | Drill Tool D7.8 |
| L12  | Contouring D2 (R.)      | 416020-MEGA-T (JH416) [SECO] | Ball mill D2 | L1.26| Reaming D8             | 16 2900 [Hoffman] | Reamer D8 |
| L13  | Contouring D2 (R.)      | 416020-MEGA-T (JH416) [SECO] | Ball mill D2 | L1.27| Drilling D9.8           | 11 3150 [Hoffman] | Drill Tool D9.8 |
| L14  | Contouring D1.5 (R.)    | 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 | L1.28| Reaming D10            | 16 2900 [Hoffman] | Reamer D10 |
| L15  | Contouring D1.5 (R.)    | 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 | L1.29| Face Milling (R.)      | ON6806R00 [OCTOPLUS] | Inserts 45º D63 |
|      | Face Milling (F.)       | 416XL015-MEGA-T (JH416) [SECO] | Ball mill D1.5 |      | Face Milling (F.)      | ON6806R00 [OCTOPLUS] | Inserts 45º D63 |

8. Production and analysis of results – CAM 1
CAM 0 is tested with the production of a first trial die half. An observation is made that the tool is hardly removing any material (small amount of chip produced), meaning that the previous operations have left too little available material to remove, causing a negative effect on tool and part. Also, another observation is that some of the operations were using the reduced speedrate in a large percentage of the process, which meant that the process was much slower than what it could be. Some conclusions are obtained to be implemented in a new CAM iteration (CAM 1). These are:
- Reduced feedrate is set to 1/3 of Axial feedrate, as opposed to the 100 mm/min value.
- Face milling (finishing) axial is reduced.
- Allowances are set for every cavity contouring step (starting at 1 mm). This way, if a small thickness layer exists between operations, the smaller tools will have enough material to remove.

9. Production and analysis of results – CAM 2
CAM 1 is tried out now in a new part. The allowance left between each of the contouring jobs makes for a better final surface finish. However, a problem is encountered in the machining of the channel that joins the riser with the cavity. The D1.5 mm ball mill breaks inside the channel because it gets caught in the chip produced by leaving an allowance. Changes in CAM 1 implemented in CAM 2 are:
- External cooling is applied to the whole process. This way the accumulation of chip in the cavities is avoided as well as a lower working temperature.
- In general, the axial speed for D1.5 mm ball mill is lowered.
- Specific for the channel operation 1.1.16, a new usage of the tool is created in which the feedrates are much lower than in the other operations, since the tool is exposed to tougher working conditions.
10. Final part and conclusions

The implementation of CAM 2 into the die can be seen in Figure 11, which shows a successful manufacturing of it, as well as Figure 12, which shows the result of casting the Oloid with the mold. Some conclusions that can be drawn from the whole project are:

- Sources of potential error in the project are the usage of sand casting method for the testing of the parts. Also, for instance “human reliability” like in the measuring of the tools or the usage of eyesight. But the most important human factor would be that of the “design decisions” taken, based on objective factors but with a clear subjective component to it.
- As stated all along the project, some decisions were made that were driven by economical aspects, availability of material etc. but even though considered, they sometimes led to not the most optimal outcome, such as in the materials or resources chosen. Other more costly options would have created a better end piece but were not viable or logical to pursue.
- As already explained in the methodology at the beginning, even though the workflow can be initially outlined, it is a process open to change. One of the main objectives of this thesis was to understand and observe this workflow. It is only now, in the conclusion of it, that we are fully able to look back and understand its evolution. What initially was merely a process of: research, design, test and iterate, turned into: design of part, then design of mold, then test and iterate. The fact that instead of simply machining the final part it was decided to cast it, adds a new dimensioning level to the process.

Even though this was already considered from the start, the level of iteration to which first the part, then the die (gating system) and then the CAM were subjected to, were more so than expected. Also, many more changes and tests could have been done to perfect the part and process, but a balance between resources and outcome had to be set.

![Figure 10. Tool direction.](image1.png) ![Figure 11. Final die.](image2.png) ![Figure 12. Final part.](image3.png)

Acknowledgments

This project has been developed under the supervision of Prof. Dr.-Ing. Roland Heiler and Prof. Ing. Piera Maresca, but also with the guidance of the laboratory engineers Dipl.-Ing.(FH) Göran Estel and Dipl.-Ing. Andreas Radeke, whose expertise and help have been essential to the conclusion of the Oloid. I am also grateful to the ERASMUS program for giving place to this experience in the first place, allowing me to develop this project in HTW-Berlin.
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