# Cast in Steel

## Technical Report of

**"VIKING AXE"**


UNIVERSITY

**INSTITUTO TECNOLÓGICO DE MORELIA**

COMMERCIAL STEEL FOUNDRY

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## Introduction

This technical report describes the fabrication of a Viking axe by the casting process in order to compare an old process of manufacturing weapons such as forged and foundry that currently plays an important role in modern industry.

The manufacture of an axe by means of the casting process is not a common activity, so it implies a challenge and development of knowledge that can serve in the future to improve the quality of other types of pieces and solve problems. The competition "Cast in Steel" promoted by the SFSA seeks to awaken the interest of the student community to enter the foundry processes and the industry that surrounds it, helping to develop skills and knowledge in sectors of the industry that have not been explored with anteriority. To obtain this Viking axe, high technology tools will be used in order to obtain an applied engineering product in all its senses. We intend to perform chopping and sharpness tests to the axe in order to evaluate its performance with modern manufacturing techniques and to contribute something to the foundry industry with the experiences gathered.

### Characteristics of a Viking axe

It is important to know the historical foundations of axes in the Viking culture to be able to manufacture a weapon that meets the requirements to be considered as a Viking axe. The Vikings were an admirable civilization that takes part of history between the 9th and 12th century, where events such as their arms development, culture, wars, among many other interesting events are dated.

There are several aspects that have to be taken into account when describing the characteristics of a Viking axe, such as lightness, weight, balance, durability, robustness as a weapon and most important for the Vikings at that time, deadly attacks.

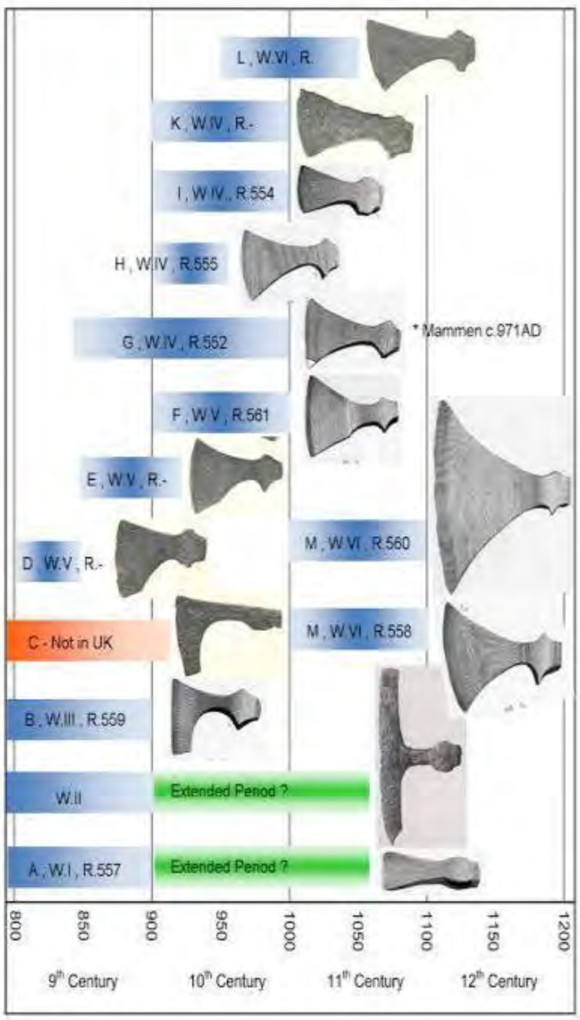



**Figure 1: Evolution of the types of Viking axes.**

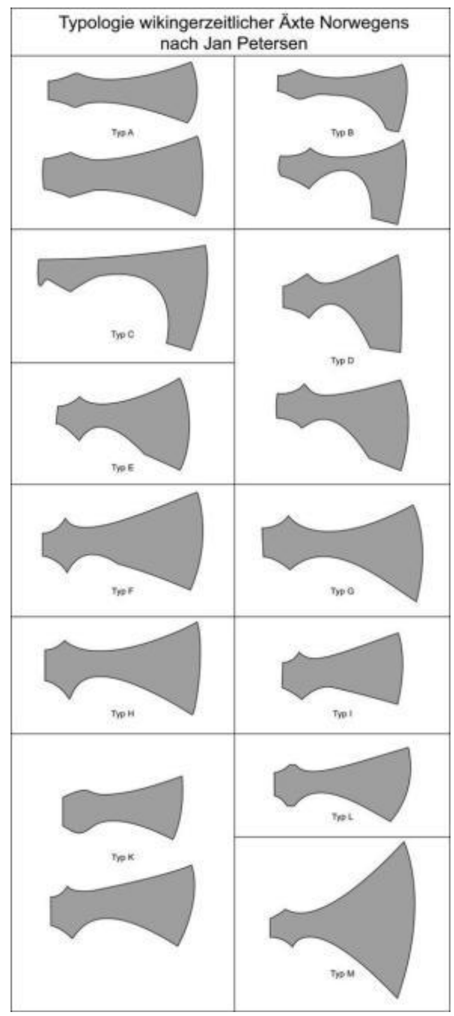



**Figure 2: Typology of Viking axes after Jan Petersen.**

In order to be considered as a Viking axe, it is important that the morphology of the axe is complied with according to historical records. As shown in figures 1 and 2, there is a great variety of geometries, which allows a wide selection in terms of design. At the beginning of the Viking era, the length of the axe blade ranged from 3 to 6 inches.

As time passed, most of the axes became longer. They could have measures between 9 and 18 inches as shown in Figure 4. An important element to classify a weapon within the Viking culture can be a symbol or engraving of its mythology. They had the function of decorating their weapons and bring luck in their travels or battles according to their beliefs.


**Figure 3: Viking and Norse symbology according to their mythology.**


**Figure 4: Measurement of the length of a Viking axe.**

In the Viking era the only method of manufacturing it, was by means of the forge, which allowed obtaining thin or thick thicknesses in the blade of the axe according to the use that was going to be given to it. But in this case due to the casting process, creating an axe with relatively thin thicknesses can generate difficulties and unwanted welding repairs, since 80% of the axe head shape is sought only by the casting process according to the requirements of the competition.

## Conceptual Design

According to the different types of axes in figure 2, the M-type axe was used as a base. Because it belongs to the last generation of axes according to figure 1. Assuming that for Vikings in the 12th century, according to their experience with the great variety of axes that were created until that time, the wars that were experienced and the problems that other types of axes could have presented, type M was designed. This would represent, as it were, an ultimatum of design that would be better than the previous types or at least with better characteristics for combat, since in the 9th century many of the axes used were to chop wood and not for war purposes.

However, something that characterized the Viking axes was its function of knocking down its opponent by pulling the feet through the hook at the bottom of the blade, as can be seen in types B, C and D of figure 2. For this reason it was decided to make a mix of two types of Viking axes, type M and type C, preserving the long and large blade characteristic of the 12th century but including an important feature for combat as to knock down the opponent to give the final blow.

**Figure 5: Viking axe types M and C.**

**Figure 6: First concept design of the combination of two types of axes.**

An addition that was decided to include into the design were symbols of Nordic mythology, which were engraved on its surface. To provide a more striking appearance and raise the degree of difficulty that represents the thin thicknesses in the casting process. One of the symbols chosen to be integrated into the axe was "Gungnir" (figure 7), which represents Odin's spear. Created by the dwarves and given by the God Loki to Odin, Gungnir had the ability to always hit his target and return to the hands of Odin once launched. The second symbol is known as "The triple horn of Odin" (figure 8), formed by three horns that the Vikings used to drink. According to Nordic mythology, Odin persuaded the giant Gunnlod to allow him to drink 3 sips of the mead contained in the horns, which when drinking all three, the mead would provide wisdom and poetic inspiration.

**Figure 7: Nordic symbol "Gungnir".**

**Figure 8: Nordic symbol "Triple Horn of Odin".**

**Detailed Design and Manufacture of the Pattern**

The detailed design represents one of the most important processes in the manufacture of the Viking axe, since vital characteristics of the process are analyzed to avoid problems and setbacks that may arise in the manufacture, as well as it defines the final product that wants to be created. It is very important to have a CAD software tool to analyze and digitally build the desired design so that it meets the characteristics set out in the conceptual design and requirements of the competition. When it comes to casting, it is known that to get to the final product, it is necessary to adapt the design according to the process that will be submitted. Therefore it is necessary to mention that the traditional casting process was selected, which is normally used in Fundidora Morelia.

The CAD software tool used for this project is "Autodesk Inventor Professional 2019", where the final design of the axe shape was created, which is shown below in figures 9 and 10.

**Figure 9: Side view of the Viking axe with a blade length of 10.7 in.**

**Figure 10: Top view of the Viking axe.**

By having the final shape of the axe, we proceed to the engineering design necessary to manufacture the piece, which will depend on very important factors in the casting process such as the pattern, the parting line of the pattern, core box, core print, drafts, surface finish, minimum wall thicknesses and stock material.

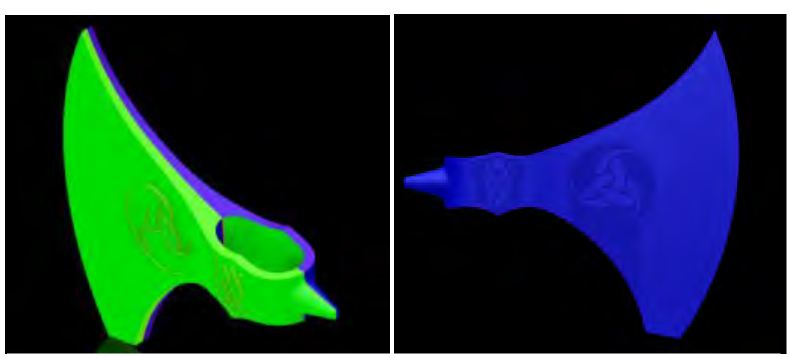


**Figure 11: Assignment of the parting line and drafts.**

The definition of the parting line in a pattern is vital to establish the stripping properties, drafts and know the minimum thicknesses of the pattern to avoid fractures caused by small wall thicknesses and fragility of the pattern material. Stock material will be required in the blade of the Viking axe and the punch in order to avoid problems in the casting as shown in figure 11 and later give the final form with grinding and cutting tools.

Nowadays thanks to technology development, you can obtain a pattern through additive manufacturing, since it can be affordable, fast, reliable and easy to use. It is only necessary to make a good pattern design to avoid assembly problems (figure 12). The most common types of problems in additive manufacturing that use materials such as PLA or ABS is that they usually do not have a good surface finish due to the size of the nozzles available in the market, however, there are other types of material in additive manufacturing such as resin that reacts to ultraviolet light and has a much better resolution per layer than the above mentioned (0.01-0.05mm). So using a combination of both types of 3D printers you can have very good results and not raise costs significantly.

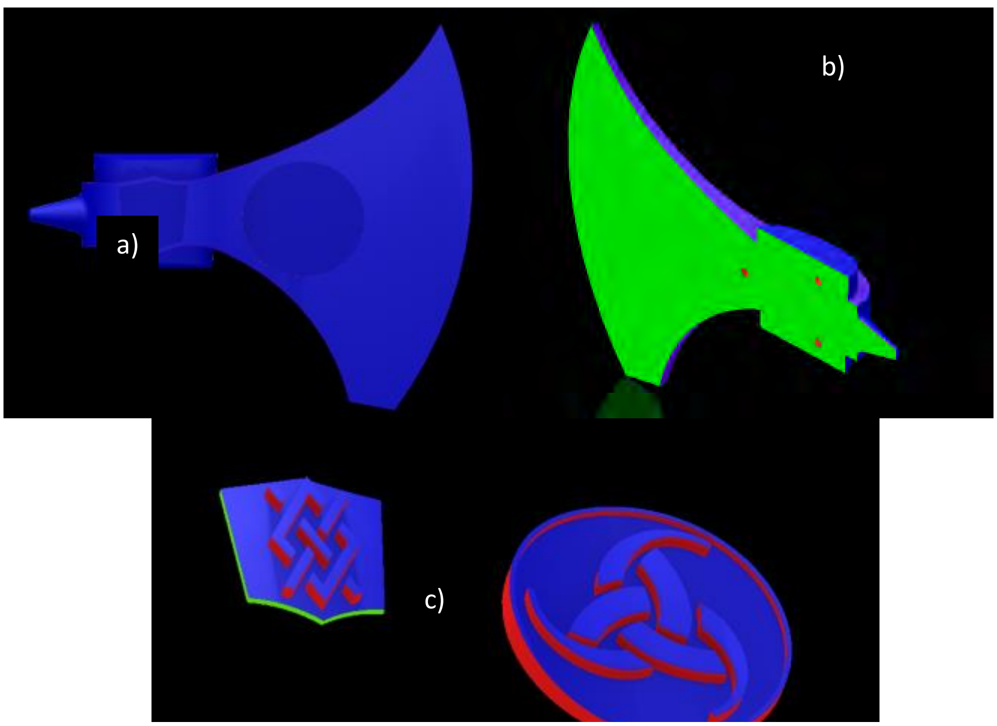



**Figure 12: 12a) Pattern design with core prints for the core and inserts (FDM) 12b) Location of guides for pattern assembly and extractors, 12c) Nordic symbols "Gungnir" and "Triple Horn of Odin" to be printed with SLA.**

It should be noted that the symbols (figure 12c) will be made in an SLA resin printer to obtain a better quality of the print and not have to repair or detail the surface finish. To generate the symbology it is necessary to include the cavity in the pattern in order to assemble correctly the inserts into the pattern as shown in figure 13.

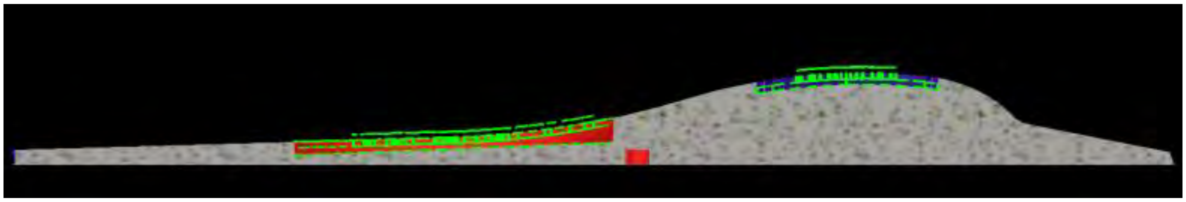
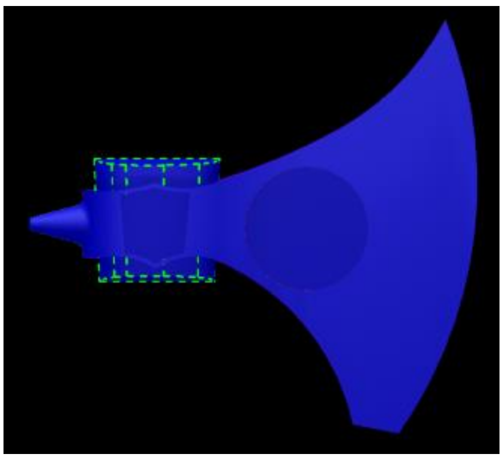


**Figure 13: Core prints in the pattern for both inserts.**

At last, in order to complete the axe pattern it is necessary to generate a 3D of the core box that will generate the cavity for the handle. Therefore, the surface of the core print will be used (figure 14) to obtain the core box shown in figure 15.



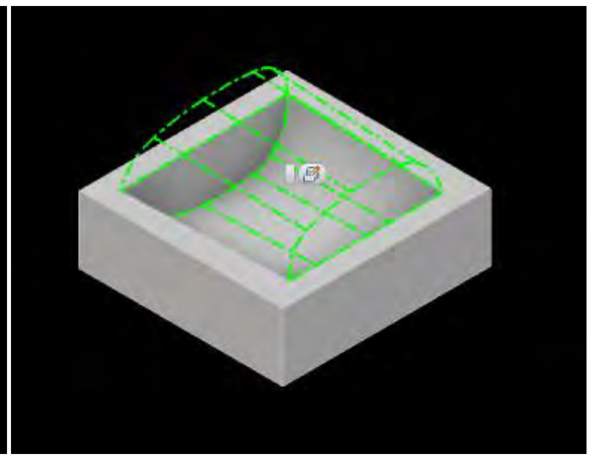


**Figure 14: Reference surface to create the core box.**

**Figure 15: Core box with 1 mm of clearance to facilitate the assembly of sand molds.**

By having the 3D models ready, we proceed to print the 7 indispensable elements to make the molds of the axe. The 2 halves of the axe type M-C, its core box, the 2 symbols of "Gungnir" and the 2 symbols of "The triple horn of odin".

**Figure 16: Prints in PLA filament made in "Titan 3D printer".**

In order to improve the surface finish of the pattern and reduce the adherence of the sand with the porous surface, layers of automotive paste are applied to regularize the surface (figure 18). Once the desired surface finish is achieved, a coat of protective paint (primer) is applied to protect the pattern and give it a longer use life (figure 18c). As mentioned above, the Nordic symbols in Figure 12c would not need repairs or modifications due to the high print quality (Figure 19). So we only had to assemble the inserts into the pattern prints and leave them without painting, otherwise, it would have presented problems when removing the sand from the pattern.


**Figure 18: 18a) Pattern with applied paste, 18b) Automotive paste "3M Quick Grip Filler", 18c) Application of protective primer coat.**


**Figure 19: 19a) Inserts of the symbol "Gungnir", 19b) 3D printer of Wanhao resins, 19c) Inserts of the symbol "Triple Horn of Odin" sectioned in 3 parts.**

Up to this point the pattern is ready to be used (figure 20), however, in the casting process it is important to corroborate the real dimensions with the nominal 3D design. Therefore, measurement tools are used to perform a dimensional inspection of the pattern, for this procedure a Creaform equipment is used (figure 21) to scan the surface, generating a mesh or a point cloud so it can be analyzed. Its positioning system is based on the use of independent references that have to be placed around and on the pattern. This means that the coordinate system of the mesh depends on where the scanning was started, which will always be an arbitrary coordinate system (figure 22a). It will be necessary to align the point clouds in order to visualize them in the best possible way and make a digital assembly of the pattern with their core boxes in such a way that the clearances presented in the pattern can be observed and corrected before they present problems in the assembly of the molds, as well as verifying that the dimensions are correct or being able to verify if there were deformations in the 3D printing. Scanning the Viking symbols was omitted because the printer resolution is known to be quite reliable and even more so for small pieces.

**Figure 20: Assembly ready for dimensional verification.**

**Figure 21: 21a) Handy Scan3D and patterns to scan, 21b) Use of reference labels on a pattern, 21c) Mesh or point cloud generated by the VX Elements software.**

It is very important to mention that the calibration and care of these high-tech equipment involves good training, since in case of having erroneous values caused by a bad calibration, can lead to errors that are difficult to detect in the future. You can see the calibration pattern in figure 21a in white. After creating the file, a point cloud is exported to work with the software "FARO Cam2 Measure 10.4" in the format ".txt", where the coordinates of all the points generated by the mesh are stored so that the software can place them in the right position.

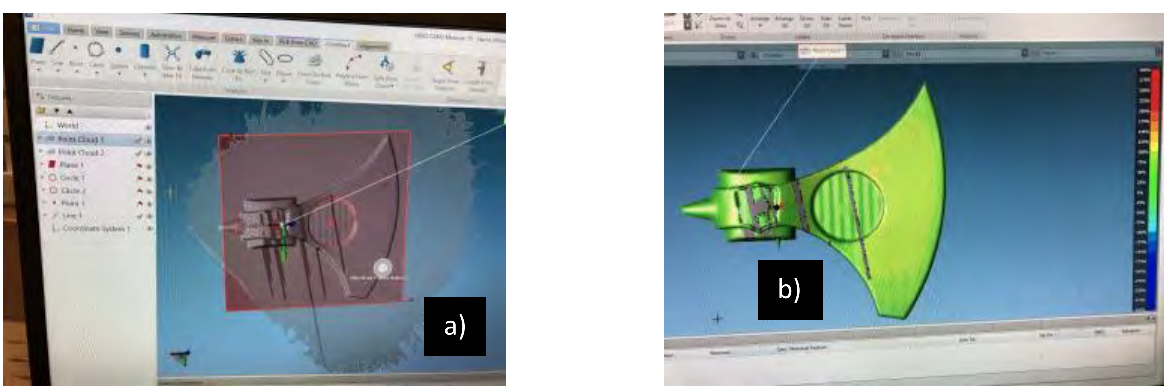



**Figure 22: 22a) Alignment method with Plane / Line / Point, 22b) Software tool CAD vs CAM (+ -1mm).**

To align a point cloud without an orthogonal orientation, you need the basic geometries as shown in image 22a, the software has the ability to build simple geometries throught the points that the user selects, when the necessary geometries are defined, it is indicated to the software which parameters of alignment shall be used, in odrder to generate a new coordinate system based on the geometries previously created.

Once the point cloud is aligned, we proceed to use the CAD vs CAM comparison tool as shown in Figure 22b, where we can enter in the software parameters the tolerance range between the surface of the 3D and the point cloud. Therefore, it shows a map of colors that represents the variation between both surfaces and allows to visualize in a very fast way the deformations or variations that can exist. In this particular case, there were no variations greater than 1mm.

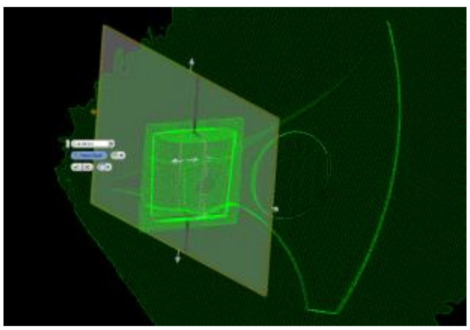


**Figure 23: Assembly of the halves of the core box.**

**Figure 24: Clearances between the pattern and core box of 1mm.**

It only remains to review the clearance between the core print and the core box using Inventor, where the point clouds generated by the FARO are already exported with the new coordinate system and assembled by means of translations and rotations, matching the core print of the patterns, boundaries of the core boxes and parting line (figure 23). As the point clouds are in their proper position, we proceed to measure the clearance between core boxes and pattern, also taking care that the surfaces do not cross each other. Figure 24 shows a clearance of 1 mm, as planned in the design of the parts so that it would not be difficult to assemble them physically. Therefore, it was concluded that the model is in very good conditions to be used and that it would not generate problems.

Before going into the selection of materials and the simulation of the solidification, this section includes the elaboration of the handle for the axe.

**Figure 25: Side and top views for the handle of the axe with a length of 28 in.**

In order to manufacture the handle with the geometry built in Inventor, scale-size templates were printed on tabloid-sized sheets to be used as a reference and to cut the ash wood which is highly recommended for baseball bats, so for an axe it would also be functional. As shown in figure 26, the templates have a reference line to continue with the profile and make 4 cuts in the automatic bandsaw to the big piece of ash.

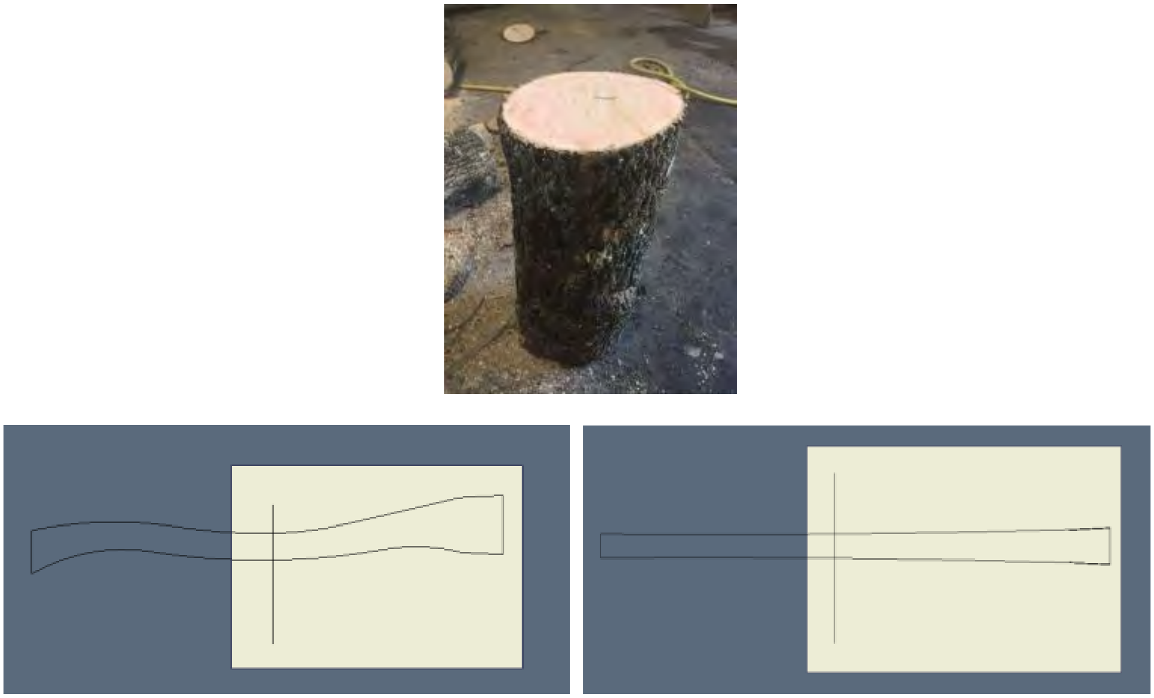


**Figure 26: Raw material (ash) with 6 in radius and 1:1 scale templates for cutting reference.**

It was necessary to remove the stock material (figure 27) and give the relevant spokes to improve the finish of the handle and provide a better grip in the palm of the hand. It was decided to inlay the natural ash wood with a semi-matt tone to provide a dim but visible shine. One of the characteristics for which this type of wood was chosen was because of its great resistance and lightness. Once the head of the Viking axe is obtained it will be necessary to gradually engage the upper part of the handle with respect to the axe cavity. The handle is designed to have a secure axe and make it fit starting from the bottom of the handle, making it impossible for the axe to be released upwards, which would be dangerous. Wood material was removed until it reached the design position, so that it would fit snugly.

**Figure 27: Preliminary axe handle without ink or fillets.**

**Figure 28: Axe handle already with spokes and a dark brown ink coat.**

**Selection of Materials and Casting Simulating Software**

There is an immense variety of materials that could have been chosen to have an optimal performance, so this is probably the most important part of the process because it defines the mechanical properties of the axe. None of the above seem to matters, if a material that does not meet certain characteristics is chosen. However, in this particular case, the amount of metal to be poured was so low, that the heat from any material chosen would be very difficult to cast in the big furnaces. The selection of the material was made by taking the stainless steel heat with highes harddess scheduled to pour in Fundidora Morelia. Which for that case, the stainless steel A-743 Gr. CA40 was chosen, which is a stainless martensitic steel that has a high degree of resistance to corrosion and due to its relative high carbon concentration has high hardness values that can reach up to 500 Brinell Hardness with the heat treatments.

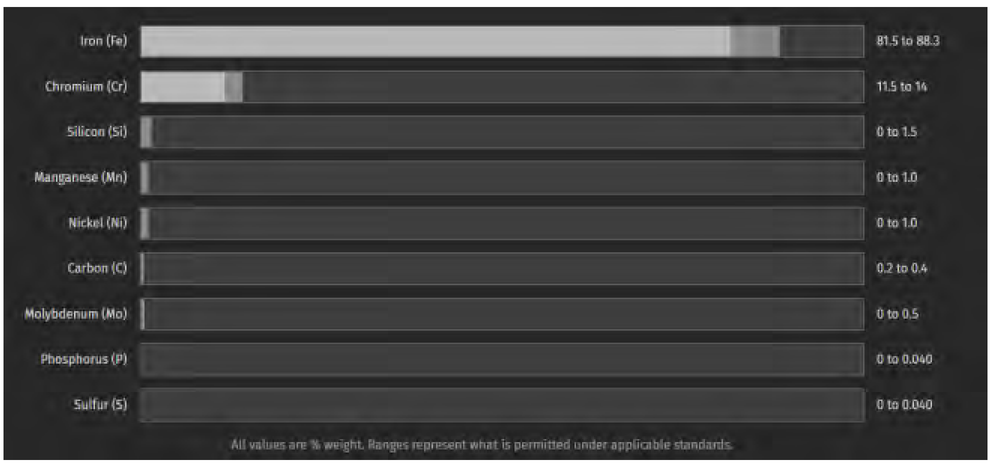



**Figure 29: Table of chemical composition of CA40.**

By knowing the material with which the axe would be manufactured, it was possible to proceed to the simulation of the solidification using the software "SolidCast 8", which was developed to simulate the behavior of the metal by analizing different criterions from the casting process, being able to show defects in the piece. It starts with the 3D of the pattern, the first step is to know how many areas need a riser to compensate the shrinkage of the material. By identifying these areas as shown in figure 30, we proceed to calculate what height and diameter must the risers be in order to have a module greater than the casting. Later, Inventor is used to generate the 3D's rigging system based on the dimensions calculated by SolidCast. It is very important to place the risers in massive areas where the metal will change density until the last moment of solidification in order to avoid defects. A very important criterion in the solidification is the "Critical Fraction Solid Time" which takes into account, the changes in fluidity that the metal has before solidifying.

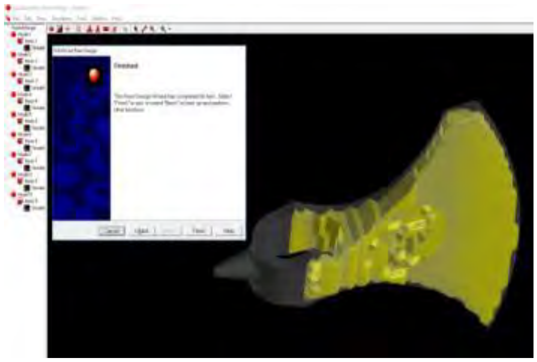


**Figure 30: Two zones that need risers to compensate for the contraction.**

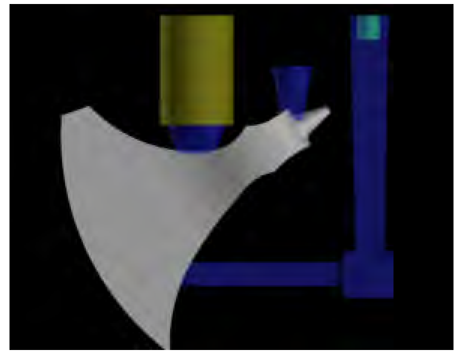


**Figure 31: Final vertical simulation # 9 where the 2 zones are fed independently.**

The idea of simulating a piece, is to run several iterations with the purpose of finding the best possible way to make that piece, avoiding the factors that lead to negative results on each iteration in order to improve on every new step, as it is shown in the two previous images where the solution is found up to simulation number 9. In some cases, although the pattern is design to obtain a mold in some specific position, that position of pouring can be changed in order to improve the casting. For example, in this particular case, the axe pattern was made with a horizontal parting line design but it can be poured on another direction for a better quality on the casting according to the vertical simulation shown in figure 33. Both vertical and horizontal simulations were simulated, to verify which direction of pouring promotes a sounder casting.

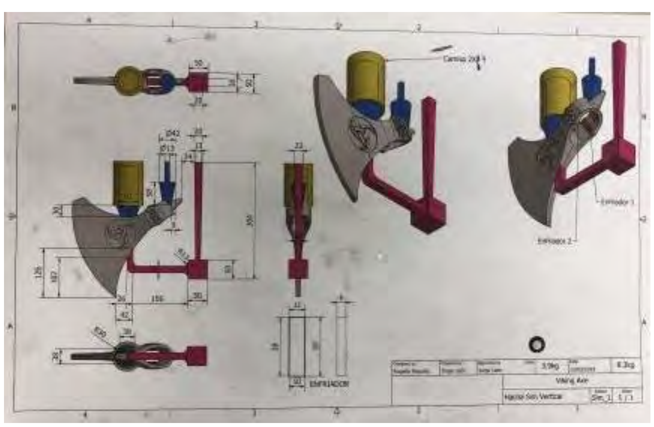


**Figure 32: 2D drawing for the elaboration of the vertical rigging system.**

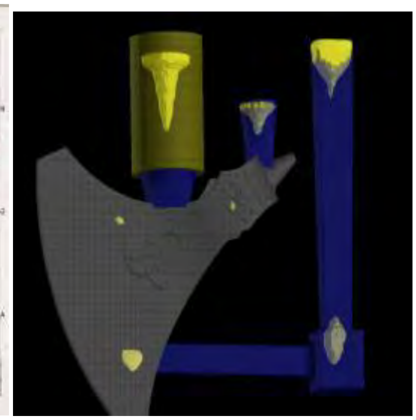


**Figure 33: Material density criterion, which shows areas of lower density.**

As shown in Figure 32, the dimensions of the risers, pads, sprue, chillers and other elements are drawn in their correct position to they can be molded with the pattern to obtain the final mold according to the final simulation.

For the realization of the mold it is specially important to respect the dimensions of the channels, gates and sprue. Because in order to have a non-presurised system (which prevents the mold to deteriorate from high speeds of the metal) the cross sections of the channels and sprue seen in figure 34 are sought to be smaller than the gates cross section for a better laminar behavior.

**Figure 34: Vertical and horizontal rigging system made with wood.**

A very important factor for this Viking axe to be considered in the position of the riser, is that it should not intersect with the profile of the symblos, since the form would be lost and the accumulated work would be discarded. Within the many tools of SolidCast, it contains a software that is devoted exclusively to the analysis of the metal flow through the mold, in order to visualize defects by some unwanted behavior in the fluid or simply verify that it works in accordance as expected.

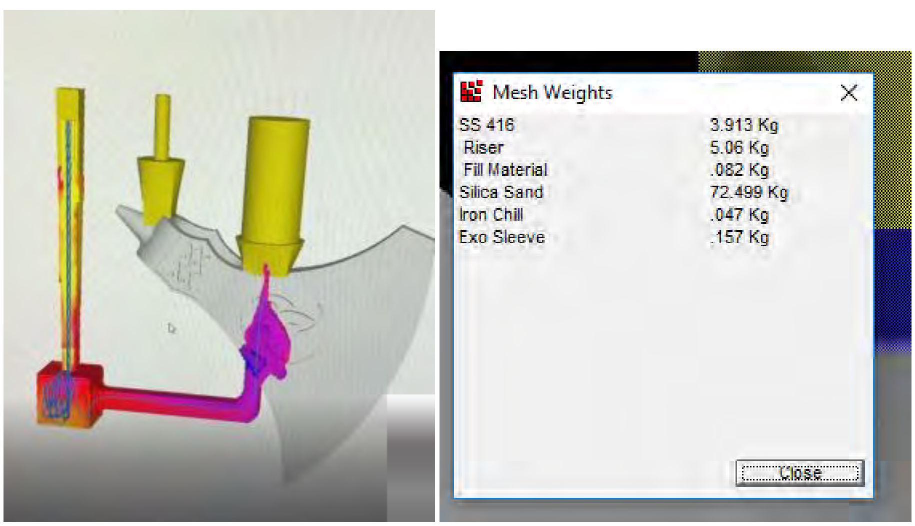



**Figure 35: Flowcast simulation of the metal filling inside the mold and the weight of the materials to be used.**

The mesh allows calculating the weights of the different types of elements that were used in the simulation, such as foundry material, risers, silica sand, chillers, exothermic sleeves, among others. This helps to predict how much each element will weight and to prepare the necessary quantities of raw material to meet the weights in Figure 35.

## Molding and Casting of the Viking Axe

The mold was made through the "No Bake" process as shown in figure 34, where some drills are manually made for venting, a refractory paint is applied to the surface of the mold that will be in contact with the metal, preventing metal penetration in the mold. If a good designed in the pattern is made, there will be no slacks in the mold and the burr shall not exist after casting the axe. Ceramic sand was used for facing, meanwhile in the feeding system and surroundings, common and recycled silica sand was used.

**Figure 34: Ceramic sand pattern and core box with refractory paint and exothermic sleeves.**

For the preparation of the casting, it was necessary to add the quantities of metal and other necessary elements to the furnace in order to obtain the appropriate percentages of chemical elements for the type of stainless steel CA40. The way to verify that the material had the correct chemical composition before pouring in Fundidora Morelia was by means of an optical emission spectrometer that calculates the percentages of elements it detects on a sample extracted from the furnace, in order to see the current percentages and know if you need to add more material, if not, the casting is ready to be for poured as shown in figure 35.

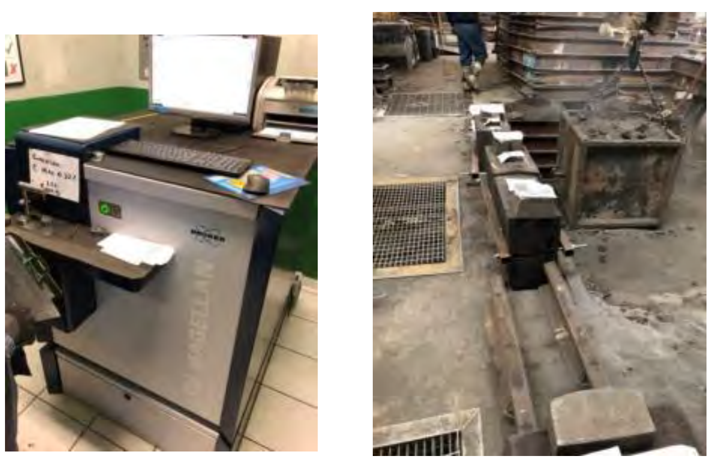


**Figure 35: Optical emission spectrometer to analyze samples and molds ready to be poured.**

Below is the last screenshot of the chemical analysis before pouring the metal, where you can see in the numbers above the range to comply with the chemical composition, while the bold numbers show the actual percentages in the alloy. In figure 36 it can be observed that the deviations of the chemical composition with respect to the nominal ones are insignificant, indicating that the process may continue.

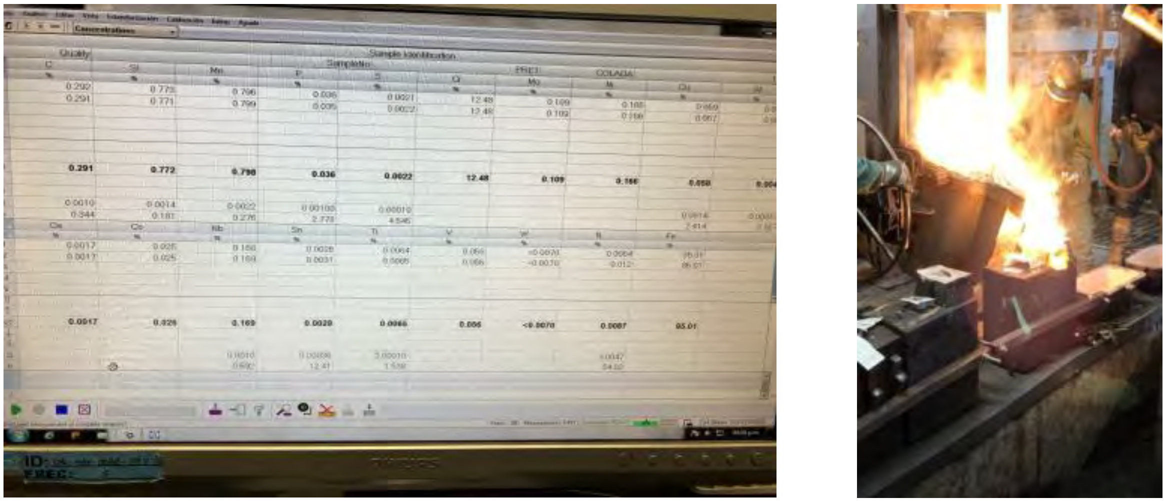


**Figure 36: Table of chemical composition results from sample number 3 and metal pouring.**

### Shake Out, Heat Treatments and Removing of the Feeding System

After the pouring was finished, the alloy was allowed to solidify in about 15 minutes and to cool down throughout the day and night to begin with the heat treatments after removing the sand from the Viking axe to facilitate the cutting of the feeding system. The cut was made with tools such as the grinding and had to be done carefully not to deform the piece due to its dimensions, which was a success to begin with a partial sharpening on the blade of the Viking axe.

**Figure 37: Vertical and horizontal axe ready for heat treatment.**

**Figure 38: Cutting and sharpening the Viking axe.**

According to the hardness measured in the piece before entering heat treatments, hardness measurements were recorded around 380 HB. The heat treatment was carried out heating up the viking axe up to a temperature of 980 °C and quenching in oil. Later it was tempered at 300 °C. Obtaining in such a way an increase in the hardness of the material as shown in figure 39.


b)

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REPORTE DE ENSAYO DE DUREZA

No.: 4771
FECHA: 30/03/2019

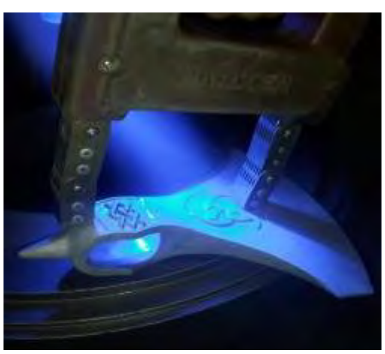
| OT | PIEZA | MATERIAL | DUREZA NOMINAL | TOMA | DUREZA REAL | EQUIPO | ETAPA DE REALIZACIÓN | A/R | P/F |
|---|---|---|---|---|---|---|---|---|---|
| 10958 | 1 | A743 GR. CA40 | >= 269HB | 1 | 443 HB | EQUOTIP | TEMPLE DE DISOLUCIÓN | A | F |
| | | | | 2 | 430 HB | | | A | F |
| | | | | 3 | 441 HB | | | A | F |

REALIZÓ: ____ INSPECTOR
LIBERÓ: LUIS ALBERTO CORDOVA SALAZAR COORD. DE CTRL. DE CALIDAD
ENTERADO: ____ COORD. SOLICITANTE

FM 122 Rev 2 05/12/2016


**Figure 39: 39a) Last heat treatment, 39b) Hardness test report of the axe, 39c) Location of hardness test on the axe.**

Once the hardness tests were completed, magnetic particle analysis was performed to verify that there were no defects in the axe due to the heat treatments or some problem in the shrinkage of the material when cooling down. Of these tests no defects or anomalies were found.



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REPORTE DE PARTÍCULAS MAGNÉTICAS

No.: 5801-1

Nº DE OT: 10958 PIEZA: 1
EQUIPO: YOKE ELECTROMAGNETIC
MEDIO INDICADOR: VIA HUMEDA
DIST. ELECTRODOS: 100-150 mm
ETAPA DE REALIZACIÓN: AFTER HEAT TREATMENT
ESPECIFICACIÓN: ASME SEC. V ART. 7 Y 25. Rev. 2017
CRITERIO: ASME SEC. VIII DIV. 1 AP. 7. Rev. 2017
AMP: 4 A VOLT: 110 V
CORRIENTE: AC INTENSIDAD: 3 KAm^-1
ZONA INSPECCIONADA: 100%

INSPECCIÓN 1
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| IND | CLASE / NIVEL (REAL) | CLASE / NIVEL (REQUERIDO) | REPARAR (S/N) | COND. DE SUPERFICIE | OBSERVACIONES |
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En caso de que al realizar este ensayo la pieza presente indicaciones, las imágenes se encontrarán en el expediente electrónico (Founderserver/ExpedientesOT)

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**Figure 40: Magnetic particles to visualize defects in the piece and its report.**

Knowing that the axe is in good conditions, the only thing remaining in the manufacture of the Viking ax is to attach it to the handle and improve the esthetics for a better presentation (figure 41), where the surface was polished and the Nordic symbols were contrasted with a dark tone. As we weigh to check if according to the calculations with the Inventor, the nominal weight of the axe with the sharpening was 3.095kg with the density of the CA40 and when we weigh it as shown in figure 42, we can notice the small variation that presents the 3D design vs the Viking axe, which means that things were made as we intended.

**Figure 41: Polishing the axe to have a better surface finish and more striking appereance.**

**Figure 42: Verification of the weight of the axe to corroborate the engineering process.**

## Final Assembly

A difficult part of the assembly process was to adjust the handle to the axe, since it was necessary to mark areas to remove material and to push it little by little to be adjusted. Finally leather handles were added to the handle to provide a better grip and decorations that the Vikings also used.

**Figure 43: Marking of area in the handle to be removed in order to assemble the axe.**

**Figure 44: Viking battle axe finished with leather decorations.**