CAST IN STEEL “THOR´S HAMMER COMPETITION”

TECHNICAL REPORT

UNIVERSITY

INSTITUTO TECNOLÓGICO DE SALTILLO

COMERCIAL STEEL FOUNDRY

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Abstract

A 5.7 pounds CA-40 stainless steel Thor´s hammer was manufactured by investment casting. This casting method was selected with the purpose of getting the best details and the most accurate similarity to the proposed design, which was based on different resources, such as Norse mythology registries and patterns, comics, and movies.

Two simulation softwares (MagmaSoft and E-Foundry), were used to predict possible issues during casting, despite both showed porosity defects due to hot spots, investment´s mold design did not change; porosity was not completely visible on the as-cast piece, but cracks appeared on the final casting.

Besides good fracture toughness, hardenability, and ductility, the selection of the steel grade was decided because of the hardness property that it could give to the hammer, which in other words could be traduced as good deformation resistance. An average of 55 HRC without heat treating was achieved, however, a stress relieving heat treating was done to the hammer at 300 °C for 2 hours without affecting hardness.

Only chemical composition and hardness test were analyzed, microstructure analysis or other mechanical tests were not done.

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1. Introduction

Mjölnir, a powerful hammer made of an indestructible metal, is the most known weapon of Norse mythology, having even representations on modern comics and movies; it has the ability to came back to his owner when it is thrown, and never fails its target, besides, only who is worthy of rise it, will possess the power of Thor, the Norse god of thunder.

With the purpose of participating on the 2021 Cast in Steel Competition, a representation of Mjölnir, the hammer of Thor, is made, and on the present report the whole process of its manufacturing is explained. It is summarized a little research of Norse mythology, where this hammer founds its origins, with the aim of supporting the finale design of the hammer, and to show the inspiration media used to made an own version of it. Then, with the support of a CAD software, a 3D model of the hammer is designed with the purpose of 3D print it, and utilize this 3D prototype to fabricate a mold where metal is going to be cast. In general, the investment casting method is used in order to get the finest details observed on the design.

Because steel possess the required properties that a hammer must have, the hammer´s head material went through different processes, such as, sandblasting, heat treating, and machining, with the objective of improve its mechanical properties and its physical appearance.

A brief analysis of the selected grade of steel, indicated that its microstructure gives the proper mechanical properties to resist several impact hits without getting deformed, and its chemical composition gives the property of getting passivated, and thus, corrosion resistant.

2. Thor´s Hammer features

The representation of Thor´s Hammer (*Mjölnir*), is one of the most known icons of all Norse mythology that symbolizes among Vikings: power, strength and bravery, and it was used as a pendant amulet of luck and protection. It is also depicted as one of the most powerful weapons in Norse mythology. Actually, there could be found many styles of this hammer (Figure 2.1), meaning that it is more important what symbolizes, rather than its physical appearance. One feature in common according to Norse mythology, is that when it was created, the hammer was short in size because of a mistake of its creator, even though, this error was not too severe because it could grow immeasurably, or even could reduce its size to get carried on a pocket. Besides this physical feature, many portrayals had been done upon the hammer, in which Nordic figures and patterns are included, some of these are explained below.

Figure 2.1. Different Viking pendants styles of Thor's hammer.

Triquetra – is made up of a continuous line that weaves around itself, which means that there is no beginning or end, and no eternal spiritual life. This symbol was originally Celtic, but with increased contact and assimilation between Vikings and peoples of Ireland and Scotland, the Triquetra and other Celtic symbols became culturally mixed. Originally, the Triquetra was associated with the Celtic Mother goddess and represented her triune nature (the maiden, the mother, and the wise old woman).

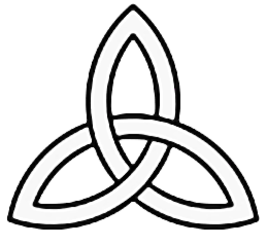

Figure 2.2. Triquetra´s representation.

Yggdrasil – It is defined as *"The Ash Tree"*. The nine worlds are intertwined in its branches and roots. Yggdrasil, then, serves as a channel or pathway between these nine dimensions that the gods can traverse.

Figure 2.3. Yggdrasil representation.

Web of Wyrd – The Vikings believed that all things even gods themselves were bound to fate. In Norse mythology, fate itself is shaped by the Norns, and the Web of Wyrd represents the tapestry the Norns weave.

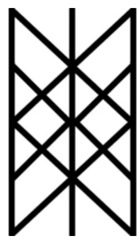

Figure 2.4. Web of Wyrd representation.

On the next figure, are represented various versions/styles of Thor´s Hammer that were utilized as reference material for hammer´s design. A common feature of all, is the use of Norse patterns that are intertwined or connected, and this gives a textured surface over the hammer, also, a handle and pommel are present in all.

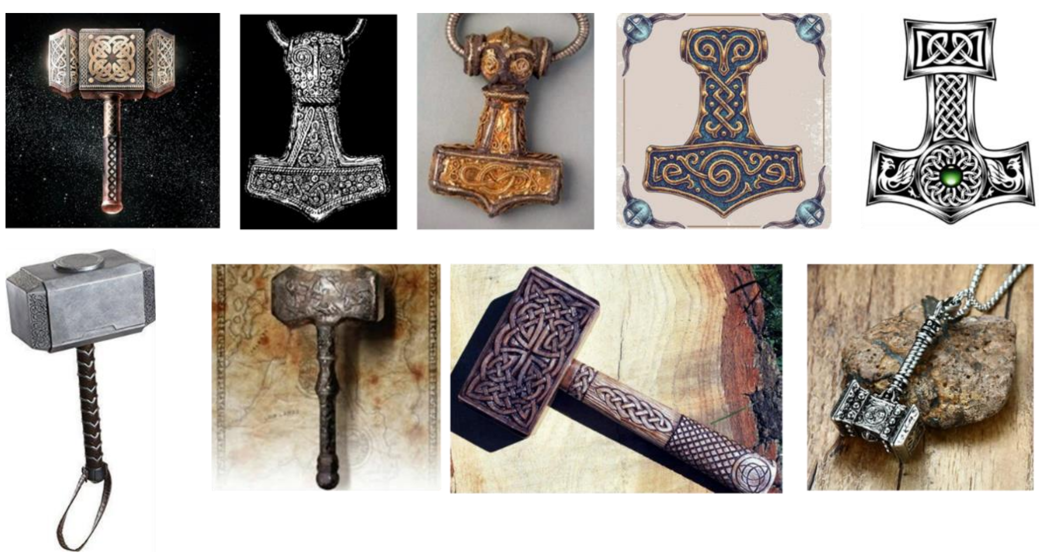

Figure 2.5. Different versions of Thor´s Hammer.

3. Materials selection and design

First of all, it was needed to clear up which kind of materials will be used on the different parts of the hammer (head, handle and pommel), so design and dimensions will be easier to establish.

Several materials were thought for the hammerhead: aluminum, steel, irons and bronze, but evaluating the options, it was concluded that steel has the best properties for a hammer. The reasons for selecting materials for the different parts of the hammer are explained below:

- Aluminum as hammerhead if well alloyed and heat treated properly, would serve principally because of its density that would make it lighter and thus, a bigger hammer could be achieved, but it is still soft and could be deformed easier compared with steel or irons.
  Because of its lighter weight compared with other metals, and higher mechanical properties (tension and impact resistance) compared with wood, aluminum, was also thought to be used on the handle; although, decision between selecting aluminum or wood for the handle, will not be made until hammerhead was casted. Further description of the selection for the handle material, is described on "Assembly" subsection.
- Bronze and brass besides they could be heavier than steel or irons, they do not possess their mechanical properties and also, as aluminum, could be deformed very easy. One of the characteristics of this kind of alloys is their attractive color, so they were still in mind to be used, but not as hammerhead material, but as pommel and handle details.
- Finally, the decision between selecting steel or iron was crucial, both have similar weight, and well alloyed and well heat treated, could achieve the purpose of a hammer. Because of its resistance to corrosion, fracture toughness, hardness, strength, impact resistance, and surface finish, martensitic stainless steel 420 grade, was selected as material for the hammerhead. Further description of this grade could be found on "Analysis" section.

The design was challenging in the sense of accomplishing the total weight of the hammer (no more than 6 pounds), so taking into account that the hammerhead will be made of steel, previous calculations had to be done, in which just by multiplying iron´s density by the calculated volume of the piece, an approximation of the weight will be obtained. Based on hammer´s head weight, further dimensions of handle and pommel were specified. Knowing the main features that a Thor´s Hammer must have, and taking inspiration on different media (movies, comics, Norse patterns and historical images) several attempts (Figure 3.1) to obtain the final design of the hammer were first drawn.

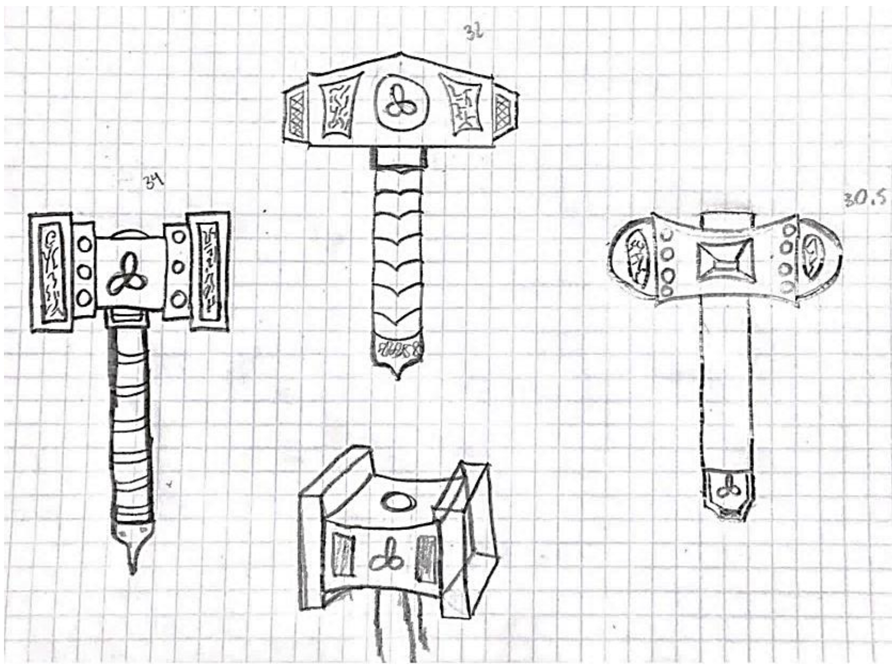

Figure 3.1. Hammer´s firsts designs.

Ease of manufacturing, total volume, and a combination of features of the above drawings (patterns, designs and symbols), were took into account in order to made a 3D model on Solidworks software. On next figures blueprints and final renders of the hammer are shown.

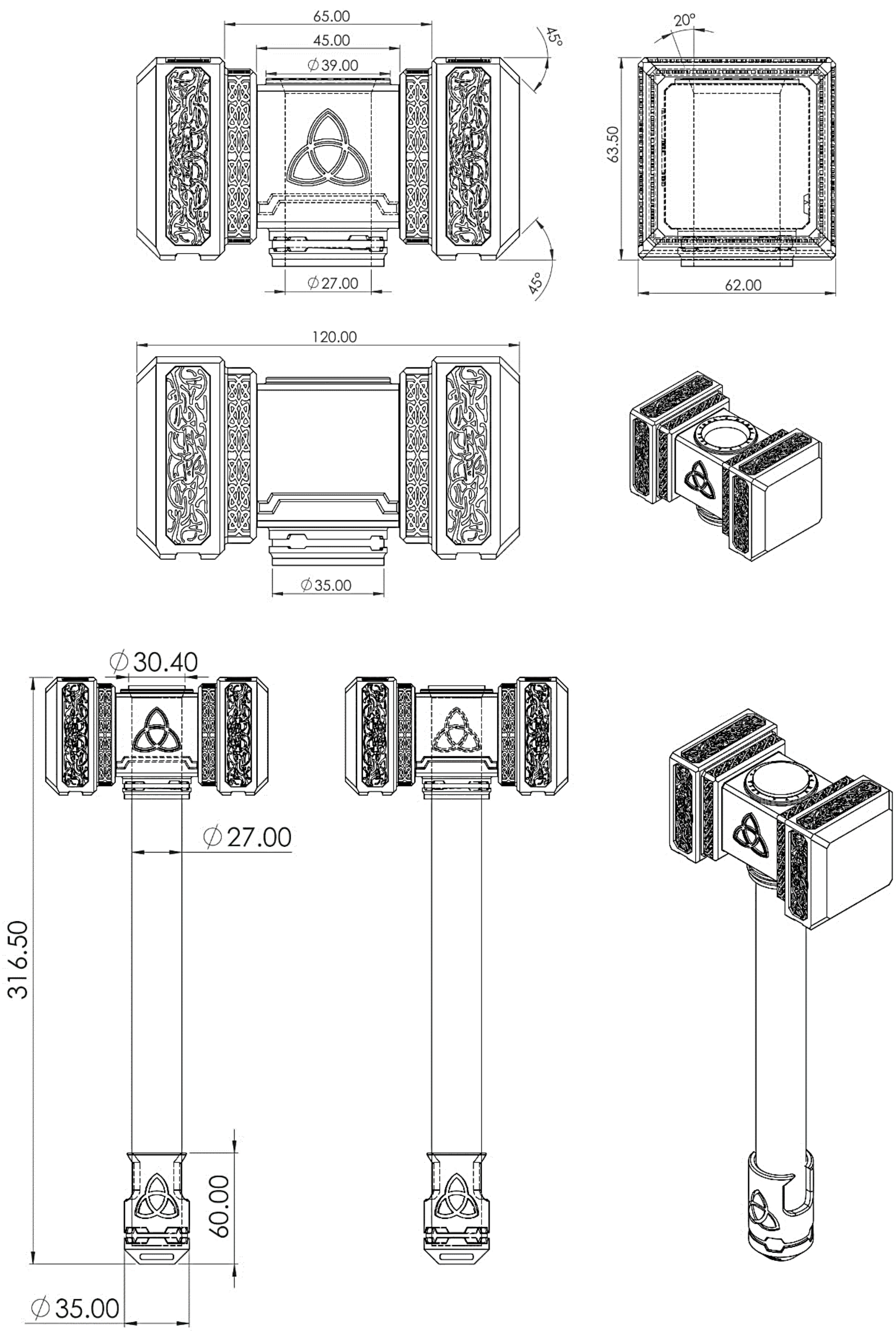

Figure 3.2. Blueprints of hammer´s final design (dimensions are in mm).

Figure 3.3. Front and top views renders of the final design of the hammer.

The final design was that form, because despite it was observed that most of Thor´s Hammer original representations have a peak on the top of the hammer, it was decided not only to get focused on just one kind of design, there were explored many other references and styles (Figure 2.1 and 2.2) to get the final sketch. There were included elements that could be seen on Marvel movies, Norse figures like *Triquetra*, and patters observed on Viking hammers, paintings, tools, and other figures such as the *Yggdrasil*, and even representations of Thor´s Hammer itself. Besides, the size of the hammer fits perfectly with the description of a short hammer that could grow immeasurably.

4. Manufacturing Process

Investment casting or lost wax process, was the selected casting method because the detail patterns and figures observed on hammer´s final design, are quite difficult to achieve by sandcasting method.

Below is detailly explained the sequence of steps followed in order to get a completely functioning martensitic steel hammer.

4.1 Molding

It was decided to manufacture a silicon rubber mold to pour liquid wax on it, and get as many replicas as possible of the 3D printed prototype (Figure 4.1).

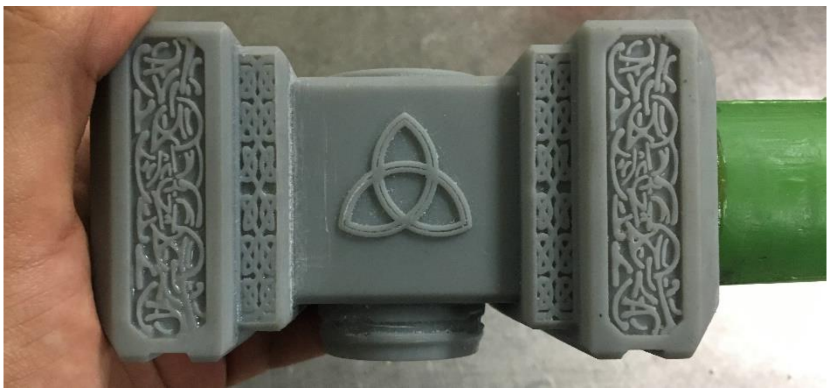

Figure 4.1. 3D printed prototype. 3D printing resin was used, so a completely 3D solid is obtained, differentiated from PLA that prints by layers.

Steps for silicon rubber molding:

1. The 3D prototype was covered with plasticine until the half.
2. A bed of plasticine is made around the prototype.
3. Metal bars were placed around the model for having a more consistent mold and avoiding the silicon rubber to spill when poured.
4. Wax bars were placed next to metal bars.
5. Three silicon rubber layers were poured maintaining a relation of 2 ml of catalyzer for every 100 g of silicon rubber. On the second layer after the first was completely dried, gauze pieces were added, and finally on the last layer, silicon rubber guides were added around the mold.
6. Wax bars were removed, and glass fiber were mixed with catalyzed polyester resin, and were placed along the mold with the purpose of creating a shell known as counter mold, this avoids silicon rubber to move when wax is poured, and makes manipulation of mold is easier.

7. Steps are repeated with the other half of the prototype, and a release agent is smeared over the surface of the silicon rubber to avoid getting paste with the other half. Demold could be done when all is completely dry.
8. Wax is poured by creating layers, and demold is done when it has dried.

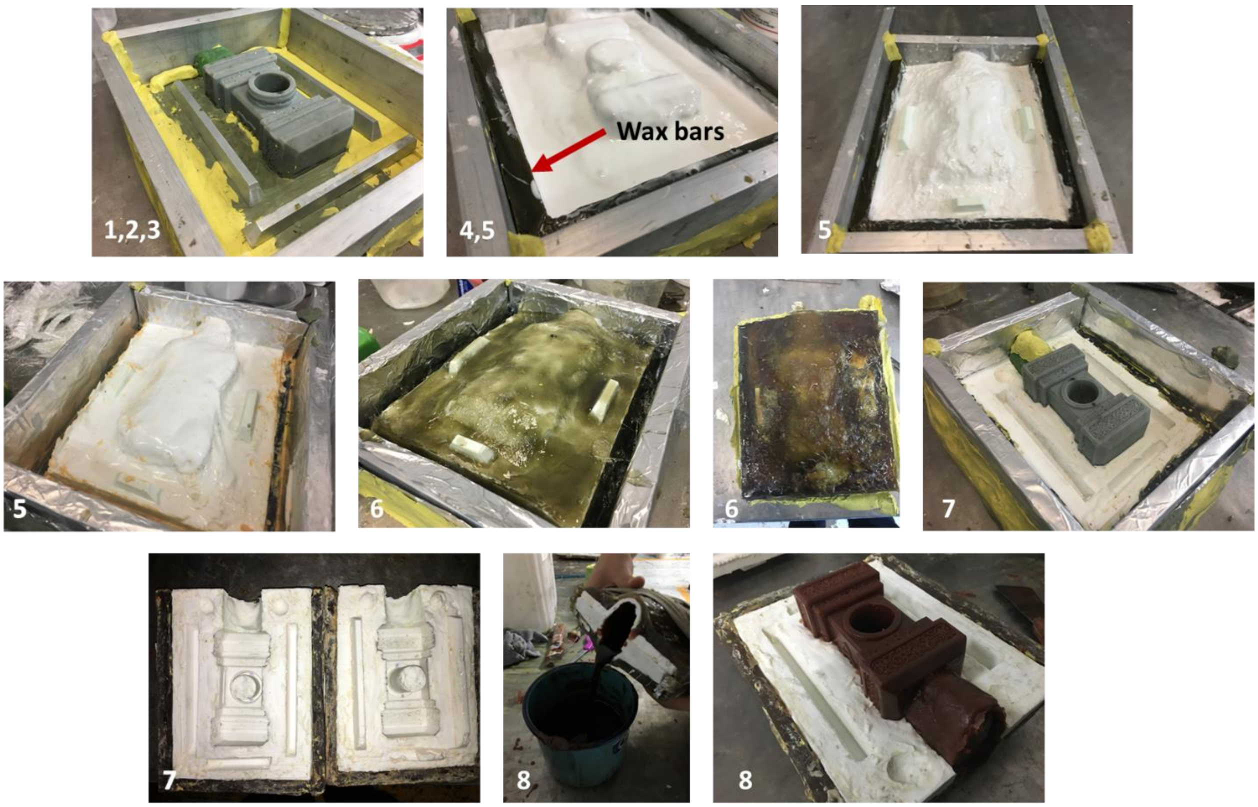

Figure 4.2. Steps for silicon rubber mold for wax casting. Numbers indicate the number of the respective step.

Taking into account the stems sizes that the industry partner manages, a 3D arrangement of the wax models was designed in *Solidworks* in order to determine if it (the arrangement), with the support of *MagmaSoft* and *E-Foundry* as metal casting simulators, could be effective when pouring liquid metal on the investment mold. Blueprints of this arrangement are shown on Figure 4.3.

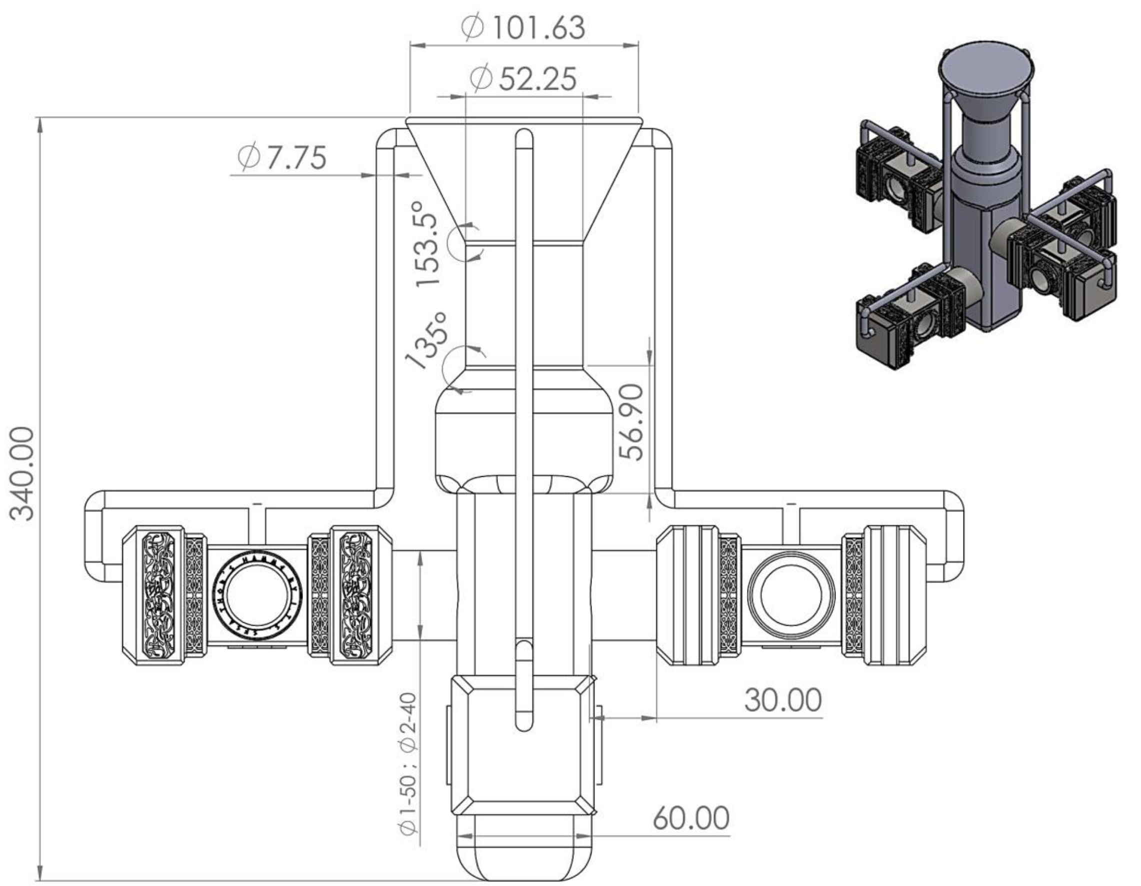

Figure 4.3. Blueprints of the arrangement designed on Solidworks. Measurements are in mm.

On simulation results (Figure 4.4), it is looked that porosity due to metal shrinkage could be found on the thicker sections of the hammer, while misruns, and blow holes are avoided on hammer´s head. From this, it could be concluded that feeders are not suitable for hammer´s casting; also, a mathematic formula ($c\left(\frac{v}{a}\right)^2$) was used in order to corroborate possible results, indicating same effect.

However, and despite possible results, it was decided to continue with the construction of the investment mold because of time delays, and feeders were made a few millimeters bigger. A great idea that came after casting was to place two more feeders where risers begun on the piece.

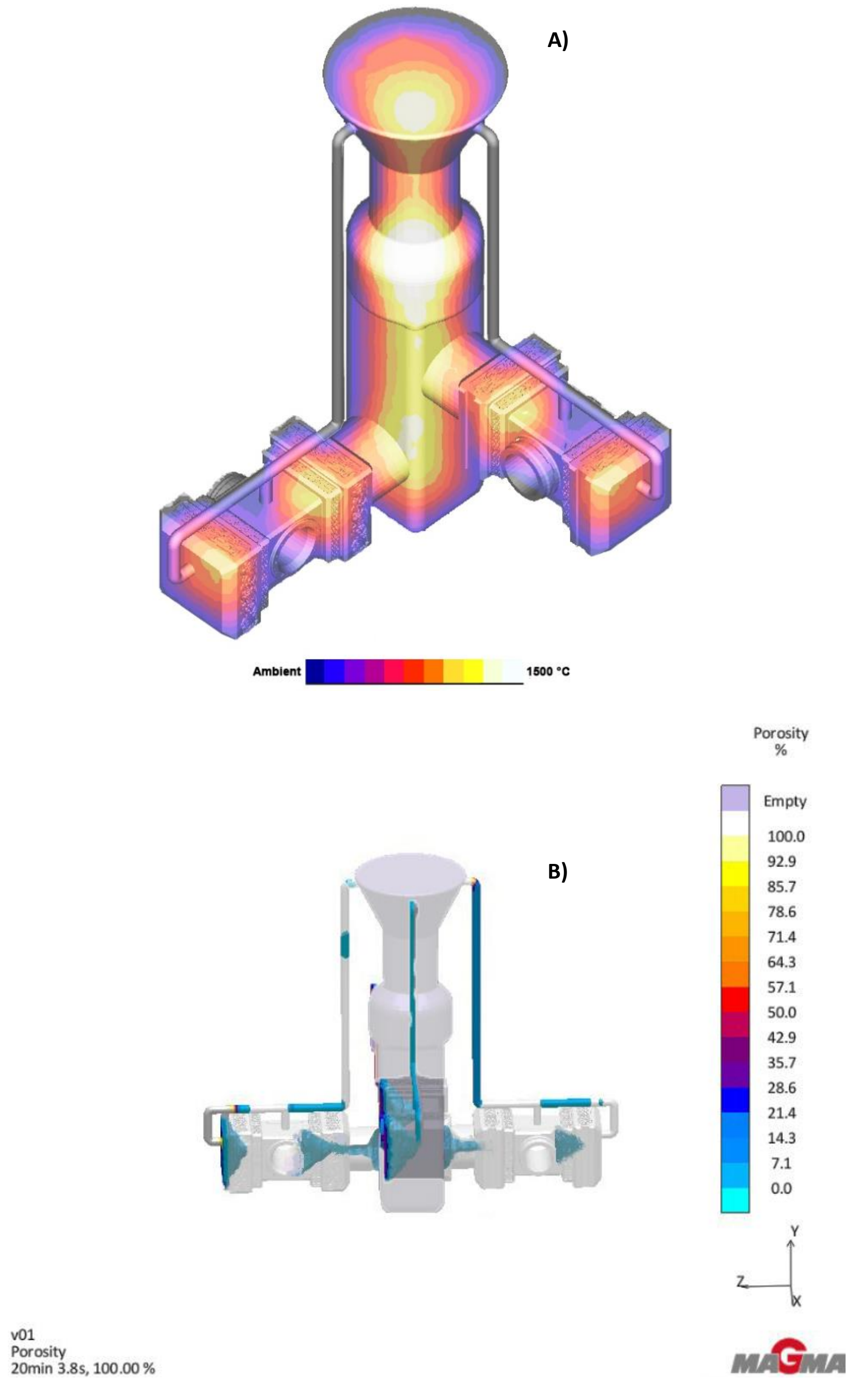

Figure 4.4. A) Made with aid of E-Foundry, indicates hot spots which are a clear indicator of shrinkage porosity, defect that is corroborated with B) MagmaSoft simulation that indicates porosity location.

Once having simulation results, it was proceeded with the making of the investment mold. Steps and images of the whole process are explained below:

1. After making the corresponding connections of the stem with risers and wax models, the complete tree arrangement, went over two steps of washing and rinsing before the investment process:
    a) First, it was washed on a perchloroethylene solution.
    b) Second, it was rinsed with potable water and dried with a compressed air gun.
2. A mixture of colloidal silica, distilled water, humectant, defoamer, and 200 silica and zircon sand mesh, was prepared in order to fabricate a ceramic slurry. A total of 8 layers of ceramic material were added on the wax tree. The elapsed time between layers (drying time), and the operations done in each one, are listed below:
    A. 2 hours – Tree is submerged on the slurry and dusted with 100 zircon sand mesh.
    B. 2 hours – Tree is submerged on the slurry and dusted with 80 silica sand mesh.
    C. 3 hours – Tree is submerged on the slurry and dusted with 50 silica sand mesh.
    D. The previous step (C) is repeated 4 times more.
    E. Final layer is called *the seal* and it is done by just submerging the tree on the slurry, this step needs 12 hours of drying.

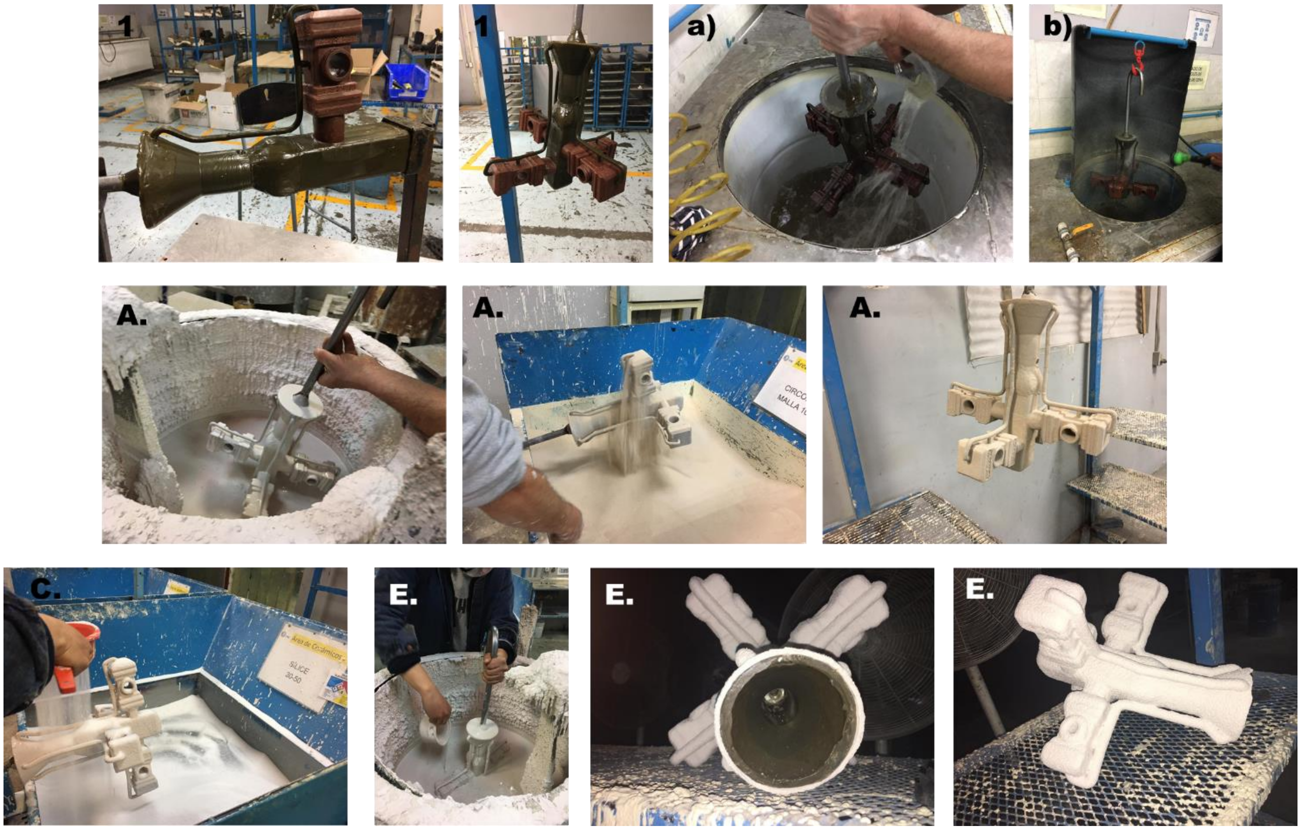

Figure 4.4. Investment process. Letters and numbers indicate the respective step.

4.2 Casting and Properties

Dewaxing was made by heating the mold at 150 °C on a special chamber, and then, mold was preheated over 1200 °C before casting.

Once preheated, mold was collocated inside a box filled with a mixture of silica and zircon sand. Scrap pieces were used to melt the alloy, and chemical balance was done with the charge of ferrochromium and ductile iron.

Shake out was not done until next day for letting the alloy to solidify at the lowest rate. After shake out, a list of the following steps is resumed:

- Sand blasting process was done with the aim of removing ceramic mold pasted traces on the metal.
- Cutting off from the tree. Feeders were utilized to corroborate chemical composition and to realize hardness test.
- Hitting faces of the hammer were machined on a milling machine in order to leave a regular edgeless surface.
- Sand paper was used to enhance physical appearance of the borders of the hammer.

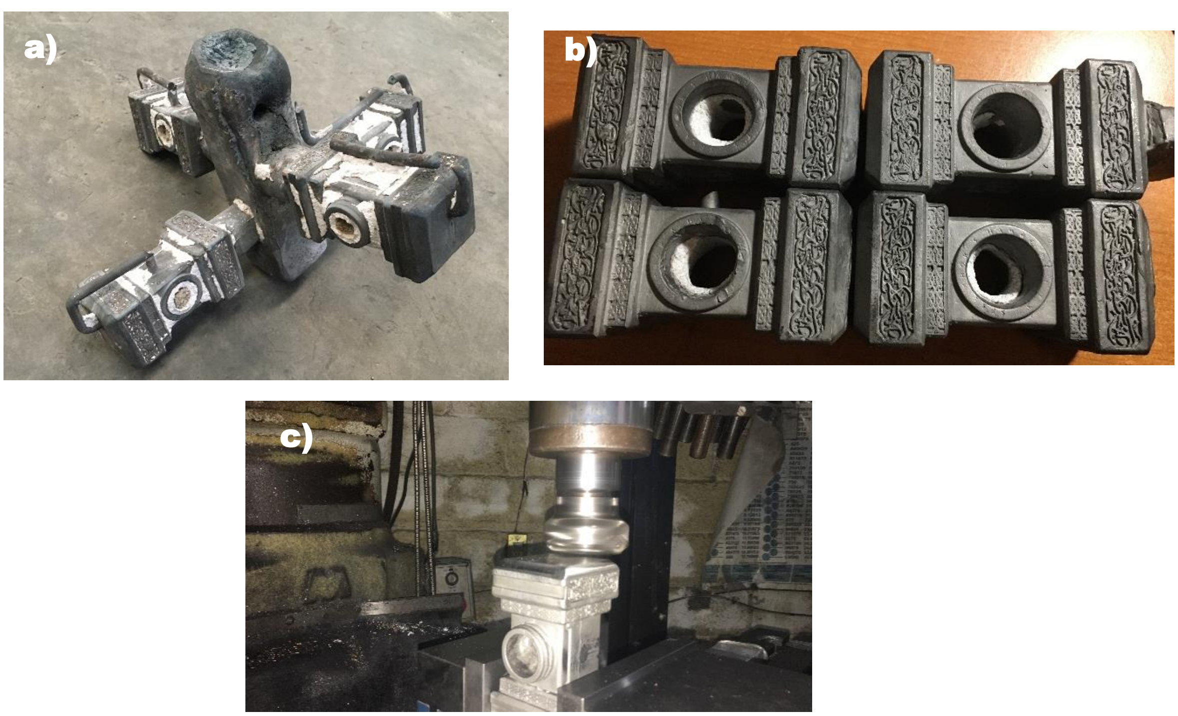

Figure 4.5. a) Shake out; b) Cut-off pieces; and c) Machined faces.

Chemical composition was corroborated on a spectrometer, 3 different tests were done, and average is represented by the symbol of <x> on Table 1. From results it could be seen that alloy is inside limits and effectively corresponds to a CA-40 stainless steel alloy, which in other words could be seen as a 420 martensitic stainless steel, difference between designations is because CA is for castings designations and 420 indicates a steel previously worked.

Table 1. Chemical composition of hammer´s head.

SPECTRO

AMETEK MATERIALS ANALYSIS DIVISION

Sample Result Name	Type	Measure Date Time	Recalculation Date Time	Origin	Method Name
SS-CA40	Unknown	3/8/2021 12:30:55 PM	3/8/2021 12:34:27 PM	Measured	Fe-01-F

Method Version	Operator Name	Correction Type	Type Corr Sample Name	Check Type	Check Status
		None		GradeWarning	Failed

Grade Verification Name	Grade Verification Similarity	Grade Search Name	Grade Search Similarity
PRUEBA PLANTA 2	0.00000 %		0.00000 %

Sample Name	Grade ID				
SS-CA40	PRUEBA PLANTA 2				

Elements Conc.

Meas.	C	Si	Mn	P	S	Cr	Mo
	%	%	%	%	%	%	%
	Conc.	Conc.	Conc.	Conc.	Conc.	Conc.	Conc.
1	0.389	0.771	0.861	0.0264	0.0168	11.75	0.347
2	0.366	0.765	0.845	0.0240	0.0168	11.66	0.331
3	0.359	0.759	0.844	0.0226	0.0164	11.63	0.325
W. Min	3.20	1.80	0.1000	0.0150	0.0050		
<x>	*0.371 -*	*0.765 -*	*0.850*	*0.0243*	*0.0167*	*11.68 +*	*0.334 +*
W. Max	4.10	3.00	1.000	0.1000	0.0350	0.0900	0.0500

Meas.	Ni	Al	Co	Cu	Nb	Ti	V
	%	%	%	%	%	%	%
	Conc.	Conc.	Conc.	Conc.	Conc.	Conc.	Conc.
1	1.10	0.0146	0.0335	0.139	<0.0040	0.0077	0.0367
2	1.10	0.0143	0.0323	0.139	<0.0040	0.0061	0.0351
3	1.09	0.0130	0.0318	0.139	<0.0040	0.0051	0.0349
<x>	*1.10 +*	*0.0140*	*0.0325*	*0.139 +*	*<0.0040*	*0.0063*	*0.0356*
W. Max	0.1000			0.00000			

Hardness test was done on a Series 2000 durometer. Samples were cut and mounted on Bakelite; test was repeated 10 times and an average of 55 HRC was obtained, which according to alloy, is within specification.

4.3 Heat Treating and Assembly

Since the grade of steel has a good predisposition to form martensite during quenching, a heat treatment process was thought: first annealing, then quenching and finally tempering; but because of cracks were presented in all hammers on the section change, and near the feeder, precautions were in mind, and the risk of quenching was not taken because of fracture or crack growing possibility. Just, a stress relieving heat treatment was done at 300 °C during 2 hours and air cooling. It was decided this way with the objective of increasing fracture toughness of the steel, and reduce the risk of a premature failure because a crack is known to be the beginning, or initiation of an inevitable fracture. Hardness was not affected by the heat treatment.

Figure 4.6. Cracks are localized around the whole edge of the section change, and only on the side of the feeder. It must be because of a hot point which solidified at the very end of the solidification process.

Figure 4.7. Heat treated hammer showed a characteristic gold color after treating.

Pommel

For the part of the pommel, a homemade casting was done. From aluminum cans, and scrap pieces of cupper and bronze, an alloy was made. Steps of molding, casting, and final details are listed below:

1. A 3D-Printed model was made of PLA layers.
2. A green sand mold was used; 6 kg of reused silica sand were prepared with 8% bentonite and 3.5% of water.
3. From the same sand mixture, a core was prepared.
4. Liquid metal was poured, and after solidification feeders were removed.
5. 80 sand grinding paper was used to retouch and enhance surface details.
6. Black and gold spray paints were used to improve physical appearance.
7. Finally, it was pasted to the handle by an epoxy resin.

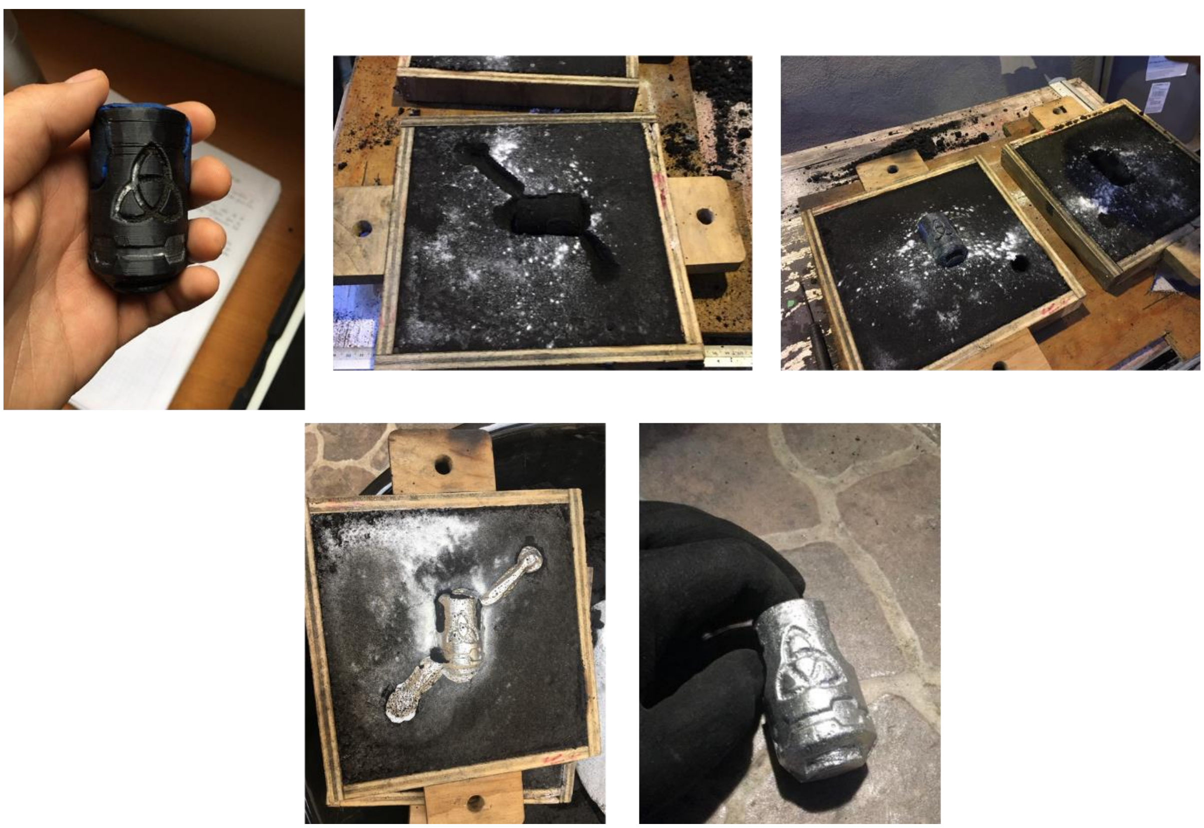

Figure 4.8. Sequence of pommel manufacturing.

Handle

A cylindrical wood bar was turned in order to achieve the diameter of the handle entrance of the hammer. Handel first entered the hollow by pressure, and two wedges were utilized to increase this pressure and to avoid hammer to shake off the handle. Besides an epoxy resin was used in order to increase sustenance and anchoring to the handle.

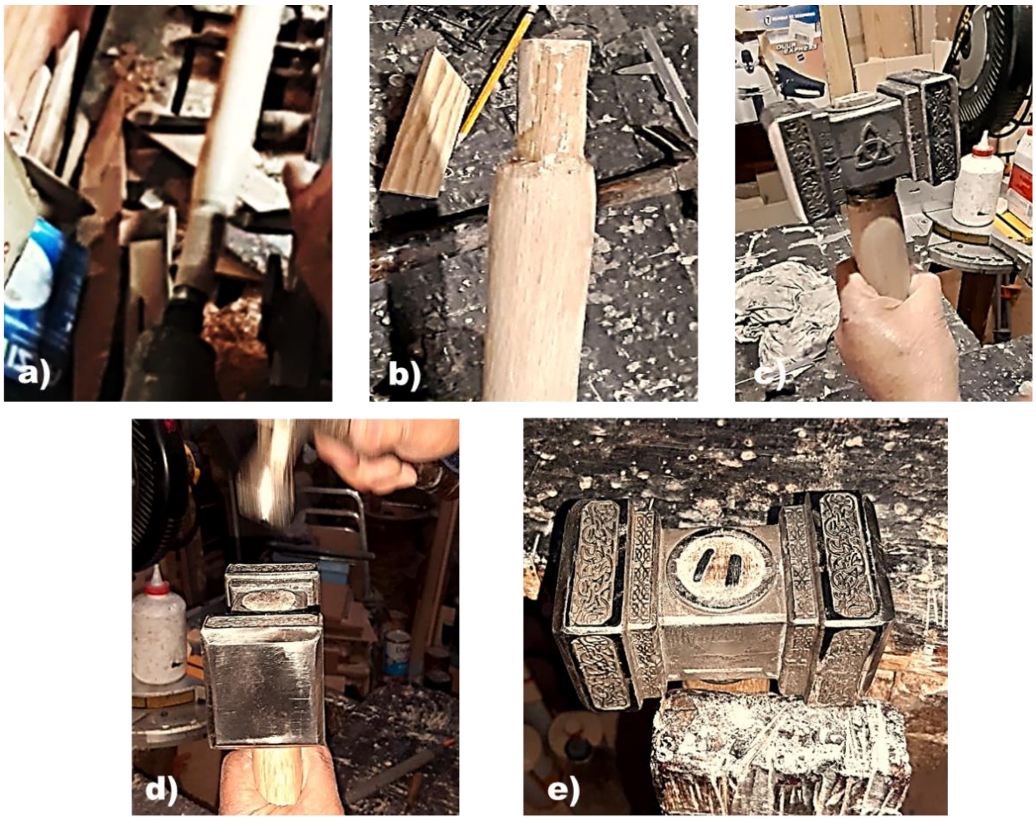

Figure 4.9. a) Handle turning, b) Epoxi resin application, c) Collocation of handle inside hammer´s hollow, d) centering handle, and e) application of wedges.

An aluminum handle was thought to be used, but because of weight limitation, wood was used, besides, it was flamed to give a better physical appearance. Each hammer surrounded 2.6 kg which equals approximately 5.73 pounds.

Figure 4.10. Finale look of the hammer.

Conclusions

- A representative hammer of Norse mythology, known as Mjolnir, was successfully made.
- The design of the hammer was based on different resources, taking inspiration from images and patterns from Norse mythology, as well as from movies and comics. It was designed in solidworks, and later a prototype was printed in 3D printing resin.
- Due to the design, the casting method that allows to achieve a great amount of detail without so much rework, investment casting process was chosen to be used.
- A mold was made to pour liquid wax, and thus have the opportunity to pour as many replicas as possible.
- A simulation was carried out in two different softwares to evaluate the efficiency of the wax tree arrangement; although the results of the simulation indicated that there would be problems of hot spots, and shrinkage porosity, the same tree design was preserved due to time issues.
- It was decided to use CA-40 stainless steel due to its mechanical properties, once it was cast, the hardness it had was evaluated, and without being heat treated, the alloy showed an average hardness of 55 HRC. The alloy has a high capacity to form martensite through the heat treatment quenching process, but since cracks were observed in all the hammer heads, it was assumed that when the alloy was subjected to cooling, it could fracture. For this reason, it was decided to carry out only a residual stress release treatment, and thus reduce the risk of fracture due to the propagation of cracks.
- Once the manufacturing process of the hammer head was completed, it was assembled with the handle, to which 2 wedges were placed in the upper part in order to avoid the detachment of the hammer head from the handle.
- A green sand cast aluminum pommel was also assembled.

Acknowledgements

The team is completely grateful with all the support and assistance of each person that helped to achieve this project.

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- Doctors Efraín Almanza and María Pérez, whose advising, aid, and support over the entire project was helpful.
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