Steel Founders' Society of America

Cast in Steel 2021

Technical report: Thor's Hammer

University:

INSTITUTO TECNOLÓGICO DE MORELIA.

Commercial Foundry:

FUNDIDORA MORELIA S.A DE C.V.

Team Members:

- *Carlos Nissim Solis Morales,*
- *Erick Pablo Pérez,*
- *Gladys Durán Durán,*
- *Nelly Paola Zavala Coria and*
- *Gabriela Mendoza Hernández.*

Faculty Advisor:

DR. FRANCISCO REYES CALDERÓN.

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ABSTRACT.

This technical report summarizes the work for the past months when we designed, casted and manufactured the Thor´s Hammer, a mythical weapon of the God´s thunder and also includes a theorical approach for the procedure done. For this project we chose the *ASTM A743 Grade CA6NM Steel* due to its mechanical properties and its good weldability. Our model was designed in Solidworks, it has a unique design not only for the details but also for its hollow structure that let us use our alloy and for the same reason we applied a welding process. The subsequent process was done in Fundidora Morelia where we casted the hammer, heat treatments, welding and the final touches like grinding and polishing as the results are shown by pictures all along the report.

INTRODUCTION.

The Thor's hammer is an interesting type of object due the properties that are attributed to. This hammer was designed based on Viking mythology and following the specifications given by the SFSA for their Cast in Steel Competition 2021. In this project we designed a unique Thor's hammer with special details and superior properties to the common.

The Cast in Steel competition challenges undergraduate students to apply their abilities to computer modeling, casting techniques and gain more knowledge during the project to choose the best material for the final product fitting on the specifications. There are mainly two rules about the design of the hammer that were given to us by the SFSA. It should not be longer than 20 inches (508mm) and should weigh no more than 6 pounds (2721.5 g).

In this technical report we described each process that we made to complete our Hammer. It started with the research of historical background of this weapon, then we justify our material selection and hammer design adding some computer simulation in casting and finally to maximize its mechanical properties its heat treatments, machined process and finishing surface done to obtain the Thor´s Hammer.

HISTORICAL BACKGROUND.

Mjölnir (Another proposal connects Mjölnir to Old Norse mjǫll meaning *"new snow"* and modern Icelandic *mjalli* meaning "*the color white"*, rendering Mjölnir as a shining lightning weapon) is the hammer of Thor in Norse mythology, used as a weapon of destruction and a sacred tool for blessing. In the Viking era of the Nordic cultural circle, the hammer was usually worn as a pendant, and Thor and his hammer appeared on various objects in the archaeological record. Today, the symbol appears in various media and is once again worn as a pendant by many groups including modern Heathenry believers.

The Prose Edda book Skáldskaparmál contains a few mentions of the hammer, including an instance of its mention in skaldic poetry. A section dedicated to kennings used by poets to refer to the god says that Thor can be referred to as "ruler and owner" of Mjölnir. The main reference offers an explanation of its manufacture by the dwarf brothers, Elitri and Brokk.

In this story, Loki cuts off the hair of Goddess Sif. After discovering this, Thor and threatens his brother if he didn't propose a solution. Loki went to svartálfar, and the son of Ivaldi made three special items for him: Sif's golden hair, Freyr's ship Skíðblaðnir, and Odin's spear Gungnir.

The dwarves Brokk and Eitri left for the forge, Eitri put a pigskin in the forge and told Brokk to manipulate the bellows and not stop. Loki turned into a fly, bothering Brokk hard, biting his hand so that he failed, they withdrew the first gift "Gullinbursti" (a golden boar); second, the fly landed and bit the back of the dwarf's neck, but he didn't respond: after inserting the gold coin, he pulled out from the forge "Delanobra", this is a gold ring, eight gold rings are produced every nine nights. Third and last, the fly landed on the dwarf's eyelids and bit him, causing the blood to cover his sight. Nevertheless, Brokk inserted the iron into the forge and pulled out the hammer Mjölnir.

Brokk left for Asgard arriving with his gifts, while they were delivered to Odin, Thor and Frey who acted as judges of said competition, the deliberation was that Brokk won the bet. [1]

The Mjolnir, the hammer of the god of thunder, Thor, and the symbol of his power, the abilities described by Brokk were that the hammer could strike any object regardless of its size; that he would never hit a false one, and that when he threw it he should not fear losing it, because no matter how far he fell, he would always return to his master, and according to his wishes, he would become so small that he could hide it in his tunic; the only defect (due to the incident caused by Loki) was its hilt, slightly short. [2] As it can be seen in Figure 1, the dwarfs brothers manufacture by accident the hammer.

***Figure 1**. The "third gift", an enormous hammer by Elmer Boyd Smith. The bottom right corner depicts the ship Skíðblaðnir "afloat" the goddess Sif's new hair.* [1]

MATERIAL SELECTION.

For the its selection we based on the mechanical properties of interest , mainly taking into consideration properties as toughness, yield strength, hardness and density. many steels qualified and them were researched in properties and applications.

We researched Dual Phase (DP) steels, some austenitic and martensitic stainless steels and comparing mechanical properties and weldability we chose the *ASTM A743 grade CA6NM Steel* that is a martensitic stainless steel its equivalents are DIN 1.4313 and DNI G-X5CrNi13-4. The chemical composition and mechanical properties are shown in Table 1 and Table 2 respectively. [6]

	%C	%Mn	%Si	%P	%S	%Cr	%Ni	%Mo
Min						11.5	3.5	0.4
Max	0.06	1.00	1.00	0.04	0.03	14.0	4.5	1.0

Table 1. Chemical composition of ASTM A743 grade CA6NM.

Other properties considered to choose our alloy were the processing properties as it excellent metal casting, the weldability even if it required a preheating and post weld heat. Also, the *CA6NM* steel presents moderate corrosion properties it has risk of pitting and crevice at low temperature and low chlorides concentration, although is not susceptible to stress corrosion cracking.

Stainless Steel, Martensitic, ASTM A743 CA6NM, CAST, TEMPERED			
Condition		Normalized, Air cooled, Tempered at 590-620°C (1094-1148°F)	
Mechanical Properties	**Min.**	**Max.**	**Units**
Young´s Modulus	195	205	GPa
Yield Strength	655	725	MPa
Tensile Strength	740	910	MPa
Elongation	20	28	% Stain
Hardness Brinell	246	272	HB
Fracture Toughness	38	55	$MPa.m^{0.5}$
Toughness (G)	7.43	14.7	KJ/m^2
Melting Point	1490	1530	°C

Table 2. Mechanical properties offered by CA6NM Stainless steel.

The applications of this steel were important to select it because are the properties in work. *CA6NM* steel is used in chemical and marine industry, Oil Fields, Petroleum Refining and Power Plants. Specific applications include compressor impellers, discharge spacers, hydraulic turbine parts, impulse wheels, packing housings, propellers, pump impellers, suction spacers, valves, etc. [4]

HAMMER DESIGN.

The design of the hammer is one of the main parts of the process due to its analysis to prevent possible complications or defects during manufacturing.

Creativity and functionality were the most important pillars in our design, that is why we decided to add engravings of symbols related to Thor that could show the astounding Norse mythology, as it can be seen in Figure 3, it shows the rays, the triquetra and some beam of light.

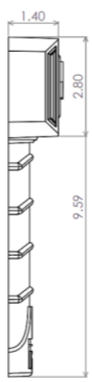

Figure 2. *Lateral view.*

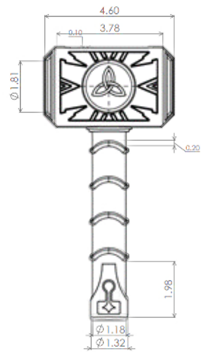

Figure 3. *Front view..*

In order to ease the making of the Hammer's mold, it was divided in half, adding 2° as draft and fillets on all edges to avoid any cracking through the small details (throughout the designing process, clearance angles were considered to attain a favorable demolding). The dimensions of the Hammer head are 4.60"X2.80"X2.80" (117X71X71mm), the handle's length is 6.7" (170.18 mm) with four grips along it and 1.18" (30mm) in diameter.

Figure 4, shows how the hammer is hollow, and the reason to do so, it is to fabricate the hammer in an uninterruptedly way which helps to reduce the weight and increase the size subjected to this procedure, the limit weight is 6Lb (2721.5g), in order to achieve a better 3D model, we used Solidworks software to designed the Thor's Hammer, and according to it, 5.9Lb (2676.2g) were obtained in weight, the thicknesses considered were 0.16" (4mm) on the hammer head and 0.4" (10mm) for the handle.

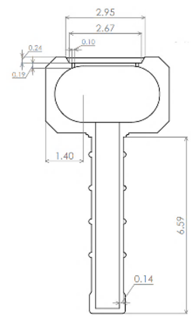

Figure 4. *Section view inside Hammer.*

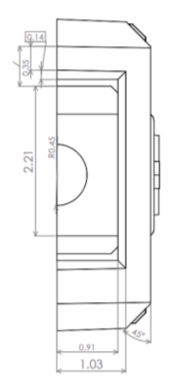

Figure 5. *Top view*

To achieve a hollow hammer, it was determined to make an aperture at the top of the hammer as can be seen in Figure 5, the top face was chose considering it would not be subjected to impacts, it doesn't affect the functionality of the design and is required less welding than split the hammer in half.

A lid was added to mantain the cavity in the hammer and it served as an aesthetic element as well in which a symbol called "Shield Knot" used by Viking culture as a symbol of protection was drawned, shown in Figure 6.

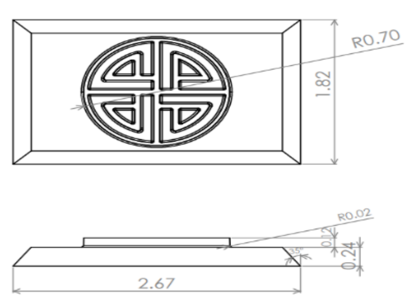

Figure 6. *Superior and lateral view form top hammer.*

The welding procedure is shown in Figure 7, there is a bezel at 60° butt without root separation with a flat finish throughout the periphery.

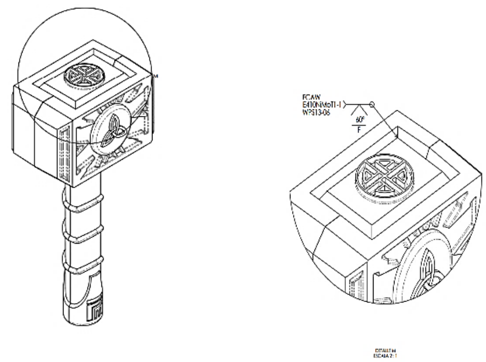

Figure 7. *Details with symbols for welding application.*

3D Modeling-Print.

Without considering welding, the weight calculated by the "Solidworks" software is 5.9Lb (2676.2g), the 3D model has the dimensions previously mentioned. Three solids were printed: the two halves of the hammer and the lid, each half of the hammer weighing 0.6Lb (269.4g) with a printing time of 13 hours, a nozzle of 5/32" (0.4mm) and an infill volume of 40%. The material used for printing is PLA (*Polylactic acid*) Filament.

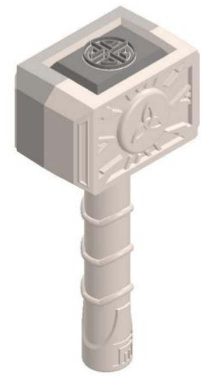

Figure 8*. Isometric view.*

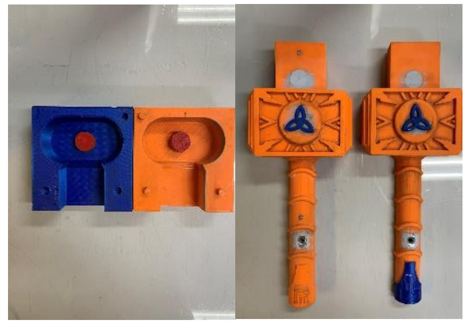

Figure 9*. 3D printed pattern with his core box for the creation of the hollow.*

Figure 8 shows the final 3D model in which it can make a distinction in colors that indicates each part printed of the hammer. The real printing of the hammer can be seen in Figure 9 (Printed pattern).

MOLDING.

Once the pattern was obtained, for the molding process it was mounted a wooden molding box, then Zircon sand was used as facing (only to cover the pattern), then it was rammed shortly and smoothly, a second layer of reclaimed sand, binder and catalyst was applied, and finally a third layer (reclaimed sand) is rammed until good compaction is achieved. The process is repeated on the other half of the model, guidelines were used so that there are no problems when assembling. The next step is to apply wash coat to both molds and core, later the core is mounted for its closure.

Figure 10. *Start of de molding process.*

Figure 11. *Half-mold in the final stage, with wash coat.*

CASTING.

In figure 12 for steel with relation Cr:Ni 3:1 the sequence of phases is observed during solidification, we have ferrite delta (δ) which is very harmful to our steel and chromium helps to retain this phase, as observed this phase is stable in the temperature range of 1450°C-1380°C (2642 °F- 2516°F), later the biphasic region (δ + γ) where ferrite delta (δ) can be retained, having an incomplete formation of austenite, so it can be concluded that ferrite is not only dependent on alloying elements (alphangens), but also cooling rates, by analyzing the transformation sequence δ → δ + γ → γ, have less time to occur if the cooling rates are increased.

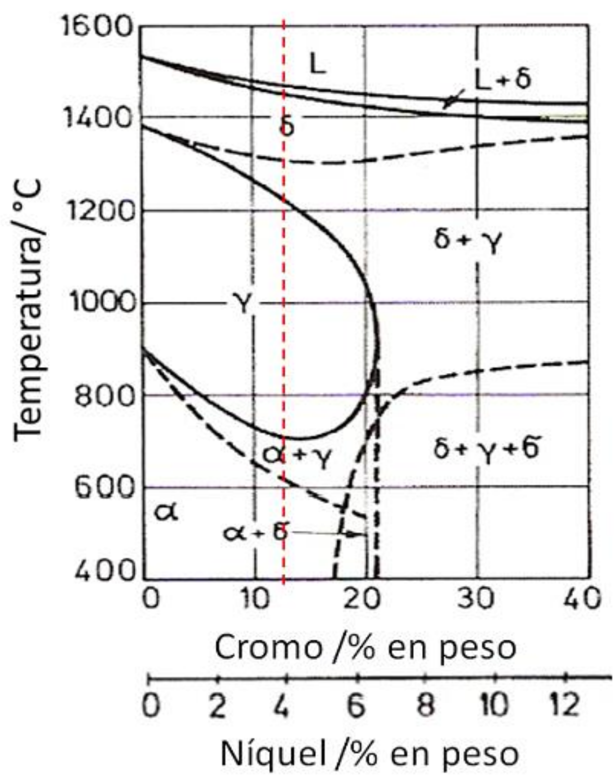

Figure 12*. Sequence of phases during the cooling of steels with relation Cr:Ni 3:1.*

Simulation.

The casting simulation was done by *Solidcast* software to define the configuration of the rigging, such as riser, runners, gates and venting, it also provides us with significant information as it is the time of solidification, temperature of casting and surface temperature.

Figure 13 shows the parameters applied to the simulation according *Solidcast.*

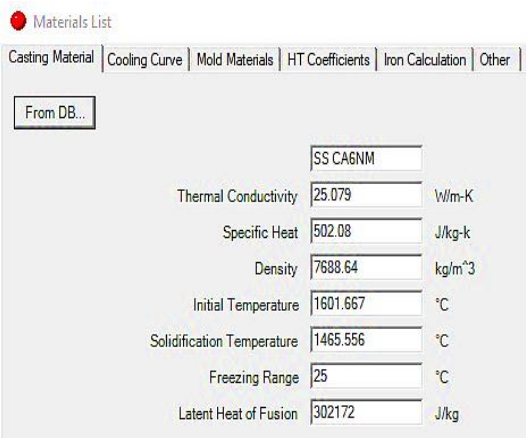

__Figure 13.__ Parameters applied to simulation.

The greatest benefit of using this tool is to prevent the presence of defects in the hammer, minimize errors, visualize mold filling and solidification. In figure 14 it can be seen blue lines that describe the steel flow during casting and different colors indicate the solidification process in which the highest temperature is the last to become solid that according to the software it occurred in the riser.

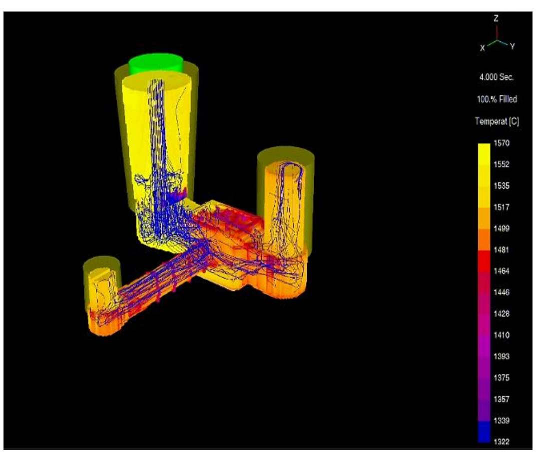

__Figure 14__. Casting simulation.

According to Figure 15, the riser and the casting channels are the last zone to solidify in the cast (*more critical Fraction Solid Time*), this reinforces the argument based on the temperature.

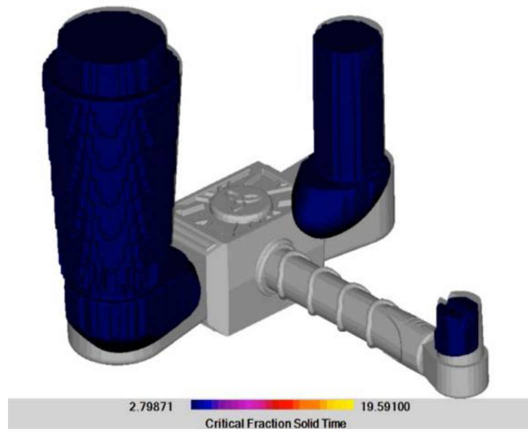

__Figure 15.__ Solidification simulation.

Process.

The metal was cast at a temperature of 1650°C (3002°F).

The final composition obtained is:

%C	%Mn	%Si	%P
0.059	**0.5**	**0.5**	**0.015**
%S	%Cr	%Ni	%Mo
0.0039	**12.53**	**4.17**	**0.486**

__Table 3.__ The final Chemical composition of the hammer.

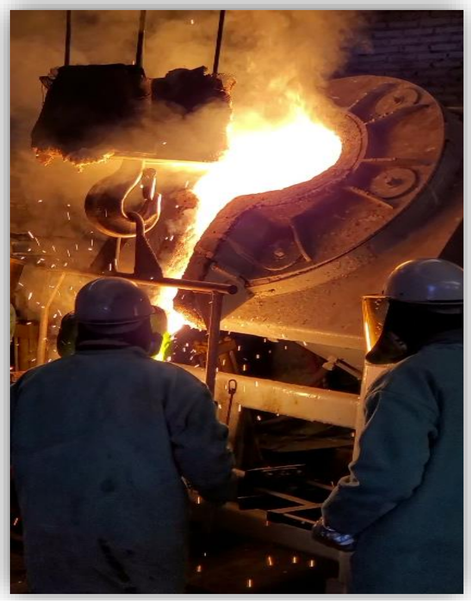

Figure 16. Casting from Induction furnace to Ladle furnace

Figure 17. Casting from Induction furnace to Ladle furnace using blue cobalt filter.

Demolding.

After pouring, the hammer remained inside the mold for about 1 hour, after this, the hammer was shake out.

Figure 18. Thor's hammer after an hour of being poured.

The riser is used for feeding the casting during the solidification period, in order to compensate for the contractions of the metal, and to prevent the formation of casting flaws and porosity. When the mold is filled, the risers are also filled and additional material is provided to allow the completion of the piece correctly; after being shake out from the mold, they are removed.

The riser removal process that uses both compressed air and heat generated by an electric arc that is set between the carbon electrode and the metal part to be cut. The compressed air oriented parallel to the electrode discharges the molten metal generated by the action of the arc, consequently making the cut.

The equipment consists of an electrode clamp with air outlet, which is fed through a hose, electric current and compressed air. This procedure was practiced for removing the risers after the hammer's casting.

Sandblasting

Sandblasting is a process of smoothing and cleaning hard surfaces by using compressed air to impulse solid particles across hard surfaces at high speed. The materials used in sandblasting (whether sand is used or not) are called explosive media. Sandblasting can quickly and effectively remove rust and oxide layers, scratches or casting marks, it can also be used to change the condition of metal surfaces by removing. Sandblasting has been widely used as a cleaning method.

This process was carried out during the surface preparation of the hammer using Aluminum oxide (Al_2O_3) as abrasive choice.

Figure 19. *Hammer and the window separated after the arc air and Sandblast process.*

WELDING.

Gas Tungsten Arc Welding (GTAW) is a gas-protected arc welding system in conjunction with a non-consumable tungsten electrode allowing us a good splash-free weld, plus no flux required. This process will be used together with ER410NiMo filler metal, based on the WPS 48/16, this process was selected in the interest of defects, such as porosity are minimal. The selected filler material is widely used for martensitic stainless steels due to the design, bears very small thicknesses, has high strength with high properties of corrosion and porosity by hydrogen.

Considering the Schaeffler diagram for predicting the present phases, the Cr_{Eq} and Ni_{Eq} formulas are shown below:

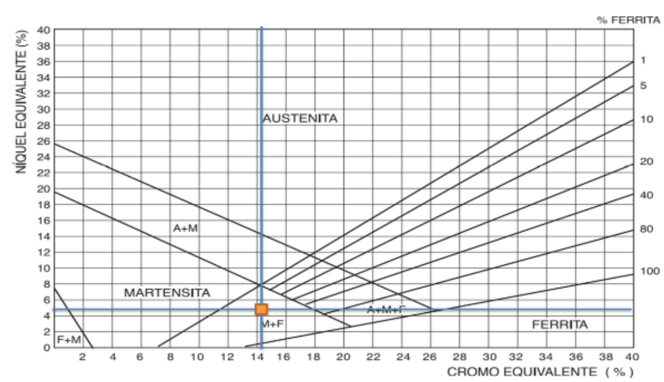

Figure 20. *Schaeffler's diagram, the orange point indicates the position of the alloy ASTM A743 grade CA6NM.*

$$Ni_{Eq} = \%Ni + (30\ x\ \%C) + (0.5\ x\ \%Mn) \quad (1)$$

$$Cr_{Eq} = \%Cr + \%Mo + (1.5\ x\ \%Si) + (0.5\ x\ \%Nb) \quad (2)$$

Cr_{Eq}=14.2 *Ni_{Eq}=5.15*

The steel considered is in the region M+F, the chemical composition is averaged, and the lever rule is used to calculate the amount of solid solution in each phase.

%Martensite =81.58 %Ferrite= 18.42

Considering the chemical composition of the filler metal to be used:

E410NiMoT1-1	%C	%Mn	%Si	%P
Typical composition	***0.04***	***0.5***	***0.21***	***0.030***
	%S	***%Cr***	***%Ni***	***%Mo***
	0.01	***11.8***	***4.60***	***0.65***

Table 3. The chemical composition of the filler material.

Cr_{Eq}=12.8 Ni_{Eq}=6.0

The base metal and the contribution metal are combined to calculate the ferrite (δ) content in the welded joint.

Since the GTAW system will be used, because of its high deposition rate, the butt layer will be located between two pieces of the same material (hammer and lid), and therefore a 50% dilution rate will be considered.

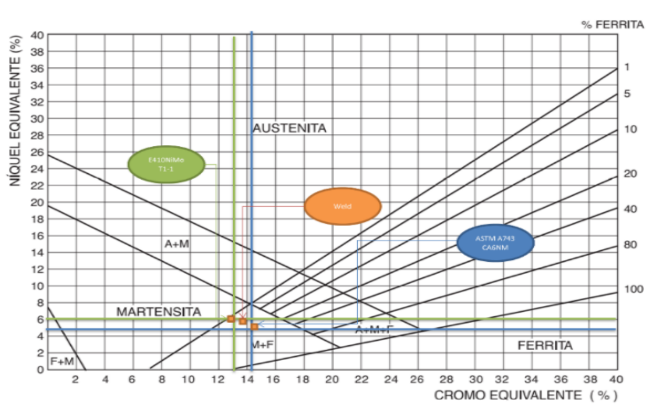

Figure 21. Schaeffler's diagram, prediction of phases presents in the welded joint.

%Martensite=89.0 %Ferrite=11.0

When welding stainless steel, the amount of ferrite is very important, because the delta ferrite can decrease tenacity and other properties by 50%.

Using Schaeffler's equivalents ratios, Seferian developed an expression to calculate the percentage of ferrite delta in stainless steel.

$$Delta\ Ferrite = 3\left(Cr_{Eq} - 0.93Ni_{Eq} - 6.7\right) \quad (3)$$

Using Eq. (1) and (2) to determine the Cr_{Eq} and Ni_{Eq} and substituting in Eq. (3) for the calculation of the ferrite delta:

Delta Ferrite = 4.7

The content of ferrite delta is generally limited to 12%; therefore, the process and filler metal is validated.

Four passes were made to fill the opening, the technique used was weave bead, the welding parameters were: 80 Amperes and 14 V and *direct-SP*

Grinding.

Visual removal of the window was done to give appearance, steel cutting discs (Al_2O_3) were used with a machine offering Approximately 8000 RPM.

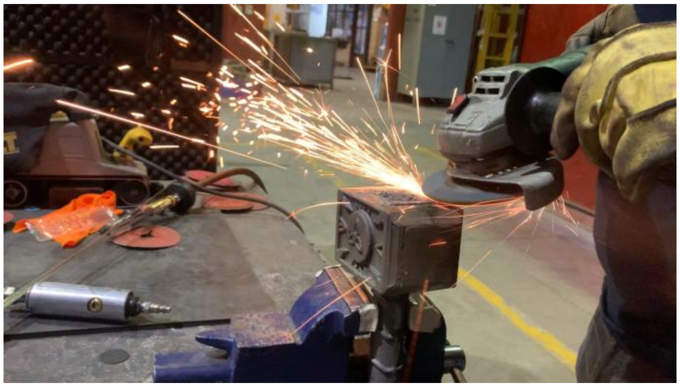

Figure 22. Elimination of the trace from the window to achieve a better appearance.

HEAT TREATMENT.

As shown in Figure 23, the steel ASTM A743 CA6NM has a clear tendency to transform to martensite with quite allowable times. Of normalized will be done at 1050°C (1922°F) using the empirical relationship "1 h/in" to promote uniformity of the crystalline structure.

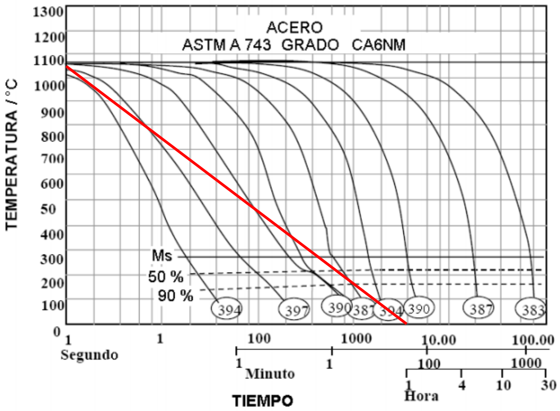

Figure 23. Continuous cooling transformation diagram.[8]

The diagram (figure 23) tells us (red line) that the expected hardness after normalization will be approximately 387-394 HB.

To calculate the time, we take the larger thickness of the hammer as 2.80" (76,2 mm) in the head, the ideal time will be approx. 3 hours of permanence.

For non-unforeseen issues such as furnace efficiency, the time spent in normalization was altered to 4 hours of soaking time,the heating ramp was 100°C/Hour (212°F/Hour) and the cooling was inside the furnace.

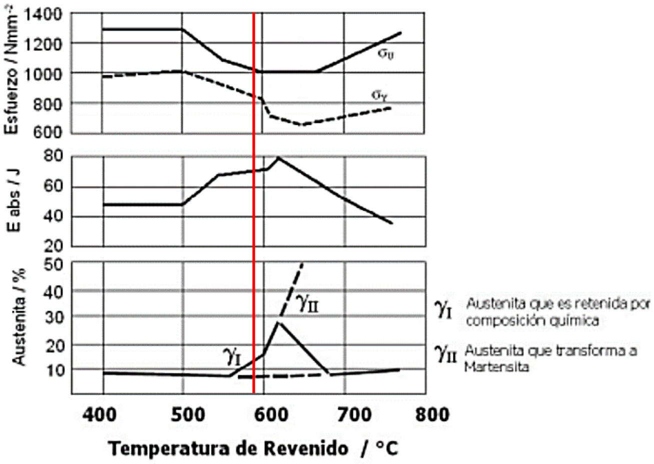

Figure 24. Types of austenite in A743 CA6NM steel with changes in toughness and tensile strength dependent on tempering temperature.

Tempering will be post-welded to 580°C (1076°F) to promote the reduction of stress and to form distributed austenite to achieve higher values of toughness the heating ramp was 200°C/Hour (392°F/Hour) the efficiency of the furnace was very high so the soaking time was 1 hour and air cooling.

Figure 25. *Tempering at 580°C (1076°F) sample No.1.*

Grade	Heat Treatment	Hardness after solutioning the samples (1100°C) 1 Hour (HRC, HB)	Hardness after Tempering 1 (667°C) 4 Hours (HRC, HB)
CA6NM A743	Furnace Cooling	28.5±0.4, 282 ± 2	26.3±1.1, 266 ± 5.2
	Air Cooling	28.9±1.1, 285 ± 5.2	27.5±1.0, 275 ± 5

Table 4. *Reference Hardness profile obtained in different cooling methods after heat treatment.* [2]

Furnace and air cooling are the types of cooling media available as the Table 4 shows that hardness decrease with the tempering and the figure 24 show how tenacity behaves with tempering temperature. Analyzing this point, we conclude that for the austenite formation (toughness increase) furnace cooling is the most optimal option.

The data shown below are conventional hammers, this to compare the magnitude of hardness and have a comparison point between Thor's hammer and a conventional hammer.

Figure 26. *Conventional Hammers with measurements values on them in HRC.*

The hardness was obtained in HB, using a conversion table the HRC values were obtained, penetration was made approximately every 5mm averaging the value after 7 tests per zone using a portable durometer. It is averaged by one getting the following table.

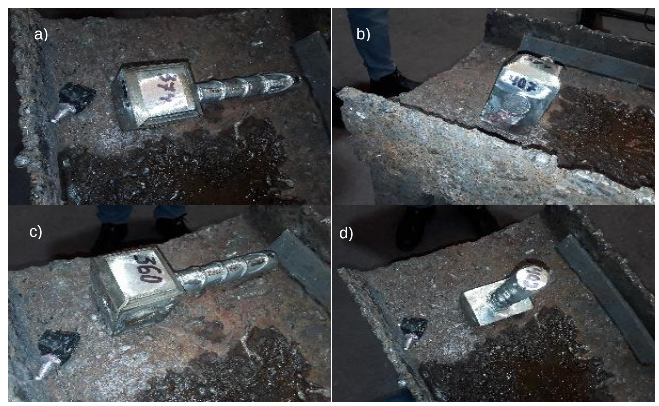

Figure 27. *a) Zone 1, lateral 1 of hammer. B) Zone 2, top of hammer. C) Zone 3, lateral 2 of hammer. D) Zone 4, bottom of hammer.*

Grade	Zone	Hardness after normalization the samples 1050°C (1922°F) 2 Hour Furnace Cooling (HRC, HB)	Hardness after Tempering 580°C (1076°F) 1 Hours Air Cooling (HRC, HB)
CA6NM A743	Zone 1	42,390	40,374
	Zone 2	44,407	42,390
	Zone 3	41,387	39,360
	Zone 4	43,402	42,390

Table 5. *Hardness obtained average in 4 Hammer's*

METALLOGRAPHIC ANALYSIS

The samples of the hammer's alloy were taken afterward performed heat treatment, they were grinded on different water sand papers (SiC) using grinding machine, water was used as coolant and turning the specimen 90 degrees in each different grit size of the abrasive paper starting in a 120 and the 240-grit size, and repeating the procedure until 2000 grit surface, this part of the process allows us to obtain a surface smooth enough to make the analysis microscopic and hardness.

Once the sample preparation process is finished, polishing begins to achieve a mirror finishing and begins with a controlled chemical attack to reveal the present phases, in this case virella's reagent was used, attacked for 3 minutes.

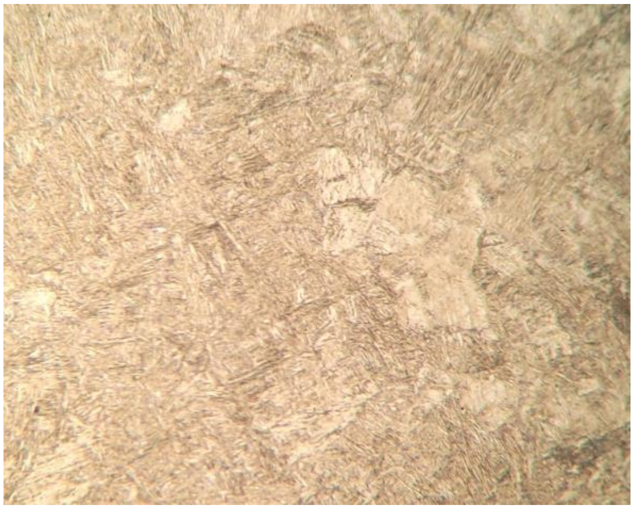

__Figure 28.__ CA6NM alloy, normalized 2h in furnace cooling at 1050°C (1922°F) Structure consists of Martensite, Virella's reagent 100X

__Figure 29.__ CA6NM alloy, normalized 2h in furnace cooling at 1050°C (1922°F) Structure consists of Martensite, Virella's reagent 400X

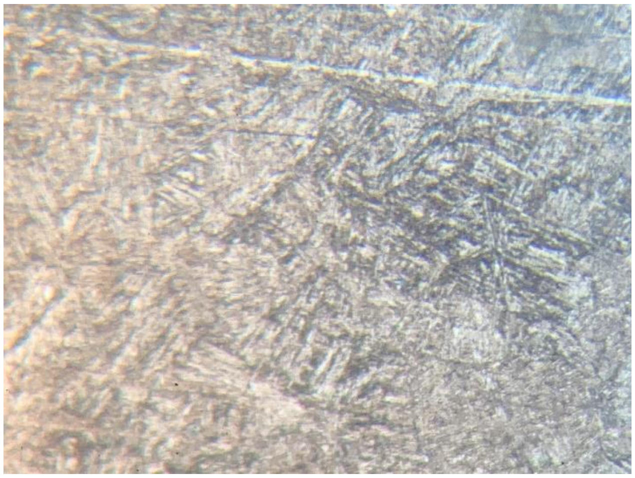

__Figure 30.__ CA6NM alloy, normalized 2h in furnace cooling at 1050°C (1922°F) and tempered 1h in air cooling at 580°C (1076°F). Structure consists of tempered Martensite Virella's reagent 400X

MACHINED PROCESS.

Drilling

In the quest to reduce weight, we chose to create a gap in the handle part, the gap has a diameter of 0.40" (10mm), the drilling was very slow since our material is too hard, the operation was done after normalizing and a conventional horizontal lathe was used, the operation lasted approximately 8 hours.

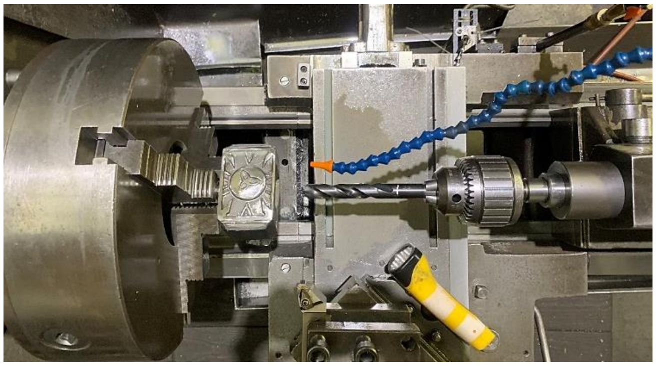

Figure 29. Drilling operation on the hammer.

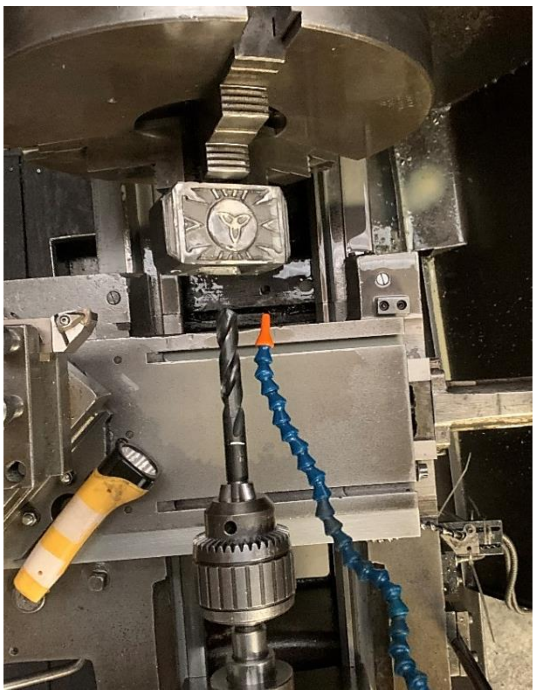

Figure 30. Drilling operation on hammer upside view.

Non-Destructive Test.

Magnetic particles.

Magnetic particles are used to locate possible surface screams, the technique is to soak the area with magnetic particles and position a magnet in a key place above the area to be analyzed, this causes the powders to move and in places of possible cracks concentrate these powders, the hammer was subject to this test, having a single surface crack , in the contact area between the handle and the hammer head, was considered a critical area as it is where at the time of impact most of the efforts are concentrated, it was chosen to repair and redo the test, in the second sampling, no superficial screaming was found.

Figure 31. The yellow line indicates the position of the possible crack.

Destructive Test.

Hardness.

It was chosen to measure the hardness of Thor's hammer and conventional hammers, to make a comparison between hammers, the results are shown in Table 5 and Figure 26.

It is concluded that the hammer has a very good hardness, this to avoid possible deformation

/penetration at the moment of impact, ensuring good toughness, the overall average of the hardness of the hammer after normalization 1050°C (1922°F) and tempered 580°C (1076°F) is 380HB (41HRC).

Figure 32. *Taking hardness on Thor's hammer.*

POLISHED.

Polishing is a very important step for any piece that should look good, it was decided that for reasons of appearance the final finish of the piece would be fully finished sandblast with polished details, (rays, triqueta and details of the impact faces).

Figure 33. *Polished details.*

CONCLUSIONS.

This project was fascinating for us not only for the approach, but also for all the work done. It gave us the opportunity to develop skills that we will need in our career, we applied our hard skills that we have gained along our years in the University, we increase hands on experience and reinforce some technical knowledge with this practice, besides, we advanced on soft skills like team work, problem solving, organization and empathy because we faced a different way to work to which we used to know. In order to maintain the safety of all the team members, we worked 80% virtually, every week we had a virtual meeting to present our updates in our areas of the project as well to solve problems as a team. We are happy with the results of our effort and we are ready for our next project!

SPECIAL THANKS.

We are so grateful to all the people involved in this project even the simplest gesture of support helped us to conclude it, but specially to the Steel Founders' Society Foundation for sponsoring this competition and let us be part of it. We also would like to thank the generous support in the manufacture of the hammer, Fundidora Morelia thanks for letting us came to your company, the use of your equipment and all the advices that you gave us, we hope work with you in future projects. And finally, thank to our department of Materials Engineering to encourage students of Instituto Tecnológico de Morelia to take this opportunity. We are proud to represent our University.

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