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Jominy Hardenability Tester with In-Situ Heating

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Senior Design Project

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Abstract

This design project of the Jominy Hardenability Tester reimagines the method of process that the Jominy test is used. With safety in mind, the Jominy tester was reengineered using an induction heater that would both limit the amount of human interaction within the test and would shorten the time in which the test took place. By placing an induction heater on the test rig, the specimen will not have to be handled while being 1500F and will allow for a more accurate reading with instantaneous cooling.

By placing an induction heater onto the test rig, the time needed to heat and stay at 1500F is shortened from previously 30 min of heating in a conventional furnace, to 2 min using an induction heater. The induction heater provides ample power to heat the specimen quickly and turn off when the specimen remains at the target temperature.

The goal of simplifying the traditional Jominy Hardenability Tester and providing a more safe method of testing steel hardness was achieved through our redesign of the Jominy hardenability Tester. With the combination of having a reduced heat up time and preventing human interaction, the way to test steel properties achieved a more condensed and safer operation.

Acknowledgement

We would like to thank and acknowledge the insight Dr. Gopal Nadkarni had in the completion of this project. We truly would not have gotten where we are without the insight and direction given to us.

Also, a major acknowledgement to Bill Steuhr and the entire Induction Tooling company for the generous donations and for allowing our group to use the resources at Induction Tooling to build our project. The knowledge and skills gained from working with the many employees has truly shown us how to be better engineers. Also, another thank you is deserved for the food graciously supplied while working!

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Chapter 1: Introduction

A Jominy Hardenability tester is a tester whose purpose is to test the hardness of a metal. This test created by Walter E Jominy in 1937 has stood the test of time for testing the material hardness after its manufacture. When steel companies make steel, the steel is made in large batches. Similar to cooking, when you test one cookie, and it is bad, it most likely means that the whole batch is bad. By providing a method to test the steel hardness corresponding to the amount of carbon, silicon, or alloy in the metal, steel and metal companies are able to test their large steel batches to identify whether the steel is truthful in the strength it is rated for. If there were no steel test, similar to cooking, the results of the final product will not be known until it is used. The importance of a hardenability test is crucial to the safety of others in all applications. This report will discuss the history of the Jominy Tester, the process involved with heat treating, and the newly designed Jominy tester that simplifies the process.

Original Jominy Tester

The original Jominy Hardenability tester is a sufficient tester that has stood for 80+ years and is a very solid and true method of how things are done. The Tester consisted of two stages; the heating of the specimen, and the cooling. The Jominy specimen is a 4in by 1in round bar and can be seen in Figure 1 and is made out of the same material as the large batch of steel being produced.

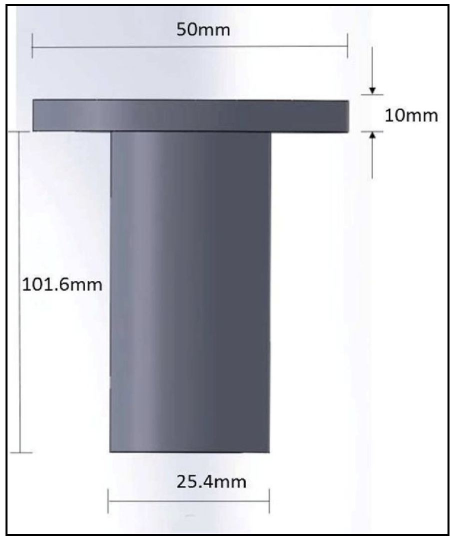

Figure 1: Jominy Specimen

The first stage of the Jominy test is the heating of the specimen. This is primarily done using a furnace. The specimen is placed into the furnace and is heated to a temperature of 1500°F. This is a process in which it takes about 30 min for the specimen to not only reach the temperature, but remain at that temperature ensuring that the entirety of the specimen is heated. This is crucial to not skew the results of the hardness.

Once the specimen is at the desired temperature and remains there, the transfer stage will need to be done. This stage is the process of transporting the specimen to the jominy tester. A pair of tongs or other transporting device will need to be used in order to safely grab and move the specimen to the jominy test. Once reaching the test, the specimen is placed into the mounting hole spanning this tank. Once the specimen is inserted, the cooling stage is under way.

The Jominy test uses a furnace to heat the specimen up to about 1500℉. This takes about 30 min to heat up. When the specimen reaches the set temperature and remains there ensuring even heating, the specimen is then transported from the furnace to the Jominy tester. The specimen is moved using handheld tongs with the extreme temperature of the specimen. The specimen is then placed into the tester and the test begins. The water will umbrella and hit the bottom of the specimen which will slowly cool the specimen. The complete setup of the Jominy Test can be seen in Figure 2.

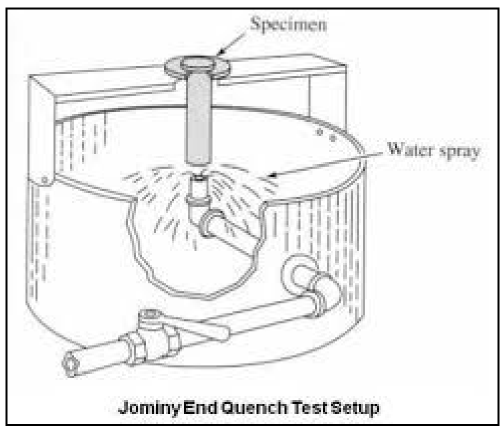

Figure 2: Jominy Test Setup

Areas of Change

Within this Jominy Hardenability test, there are areas in which can be deemed dangerous and in need of change. One process in particular is that of the transportation of a red hot metal specimen. After the specimen is in the furnace and is heated up, the specimen will need to be transported from the furnace into the Jominy tester. This method is currently using gloves and tongs to pick the metal specimen up and walk across a distance to then place the specimen into the crossbeam on the tester. This is a dangerous method using tongs to transport a red hot metal specimen. Human error is a major component to any test and can only try and be minimized. The human error of potentially dropping the metal in a classroom or in a test room is too great to ignore. Methods to combat this method must be devised to limit the human interaction to make the test entirely more safe all around.

Another area in which is in need of change deals directly with the transport of the specimen. The current method as discussed above is transporting the metal specimen across a floor for a certain distance, whatever the distance the furnace and tester are from each other. This transporting of the metal specimen causes unwanted cooling when moving the part through air. The metal when being walked at about 2mph to the tester experiences movement of air around and on the metal specimen where the temperature of the specimen is not at its intended point when the test begins. The temperature is actually lowered before it reaches the tester potentially skewing the results. This is a factor which will need to be changed to get better, more accurate results.

With the combination of the 2 areas in need of change, the determination that the components surrounding the act of transporting the metal specimen needs to be reinvented for safety reasons and for overall test performance.

Heat Treatment Process

The purpose of the Jominy Hardenability test is to test the hardness of the steel. According to Thoughco.com, “The temperatures metals are heated to, and the rate of cooling after heat treatment can significantly change metal's properties.” With the temperature and cooling rate determining the properties of the metal, the molecular structure of the material is changed.

When the steel is heated up above its crystallization point, which differs with the alloys in the steel, the molecules are in a transition state within a solid. The transition state enables the metal to be re-hardened to the desired strength for its intended purpose. The heating of the specimen to its re-crystallization temperature is known as it's austenization point, or transformation into an austenite metal. Austenite is the point in which the metal is in between solid state of carbon allowing for a more workable metal. For a Jominy test, the furnace heats the specimen up to its austenization point and holds this temperature allowing the molecules to uniformly remain in the same state. This temperature enables the molecules to grow in size for the eventually freezing of the molecules in the cooling phase. The austenization point differs for the different types of steel alloys that are tested. There are many different types of steel alloys that require different individual austenization points for the molecules to uniformly reach this level. The different steel alloys inside of steel can include carbon, nickel, chromium, silicon, and others which determine the metals ductility, brittleness, and overall strength. Once the steel specimen reaches its austenite temperature and remains there, the steel is ready for the next stage.

Once heated, the quench stage is then started. The quench phase will differ per application the steel will be used for. The different types of heat treatment are Hardening, Annealing, Normalizing, and Tempering.

Hardening or quenching is the process in which the steel is heated to austinization, then cooled rapidly either by submersion or spray that encapsulates the entire sheet. This process rapidly cools the steel shocking the molecules. The molecules, since being cooled so rapidly, do not have enough time to form back into its original crystalline structure. The rapid cooling causes the austinite molecular structure to become what is known as martensite. The difference in the molecular level of the steel can be seen in Figure 3. The martensite steel traps carbon into the steel making the steel harder and stronger but causing the steel to be more brittle.

Figure 3: Molecular steel before and after Quench Heat Treatment (www.global-heat-treatment.com)

For the process of Annealing, the steel is heated to its austinization point and held at that point for an extended time, then air cooled for use. The primary function of this process is to allow any oxygen that the steel trapped into its makeup to be brought outside of the steel to allow for the steel to be more ductile and less likely for fracturing when machining or use in its intended application.

When it comes to normalizing, the process is very similar to that of annealing however the steel is heated above its austinization point and held at the point for an extended time then air cooled. This process helps enable smaller grain size in the steel helping with strength, ductility, and overall machinability.

The last process is tempering. Tempering is the process of heating the metal below the austinite point for an extended time then air cooling it. This process allows for normal more brittle steel to become more machinable and ductile while keeping its hardness . Applications that require more carbon-alloyed or harder steels will use this process to make more complex forms while retaining the hardness required for its application.

The process of heat treatment enables the manufacturer to customize the steel properties based on its surrounding environment and intended purpose. With a jominy Hardenability Tester, the manufactures are utilizing a combination of these heat treating processes to test the steel batches to determine if the strength, ductility and machinability of the steel is correct for its intended application.

Induction Heating

Induction heating became extremely popular in World War 2 when engineers realized that axles and engine components would last longer using case hardening. To use induction heating, several components are needed; A power supply, a work head, an induction coil and water cooling system.

The power supply creates the power that goes through the coil to create the inductance. Inductance is the resistance of a circuit element to changes in current. The more power that is created, the greater the inductance becomes in the coil. With higher inductance, small or large parts can be heated up faster with even coverage across the entire part. The power supply can have many ratings and come in a variety of sizes depending on the size and thickness of the part. Along with greater inductance, the greater the power supply is needed to properly and safely provide enough electricity to heat up a part.

The work head brings the coil and the power supply together. The work head matches the impedance of the coil with the power supply. The coil is threaded onto studs of the work head. The inside of the studs are hollow to allow water to pass through.

The induction coil is a coiled piece of copper. These copper coils are normally created out of rectangular or circular tubing. The way the coil is wrapped changes how the coil performs. When talking about performance it's specifically talking about the inductance the coil creates. Spreading out the coil, changing the diameter of the coil, changing the size and shape of the coil tubes and changing the overall height of the coil all can be used to totally change the inductance of the coil.

The water cooling runs through the other three devices to make the induction system work. Water starts in a water chiller. From there it gets pumped out and goes through the power supply to chill the board components. From there the water is pumped up towards the work head. The water goes through the work head and into the coil. The water is necessary to go through the coil so the copper does not melt from all the power going through the coil.

With these four key components working together an induction system is created. Power is pushed through the coil with alternating current. This alternating current creates impedance in the coil which heats up the material inside the coil.

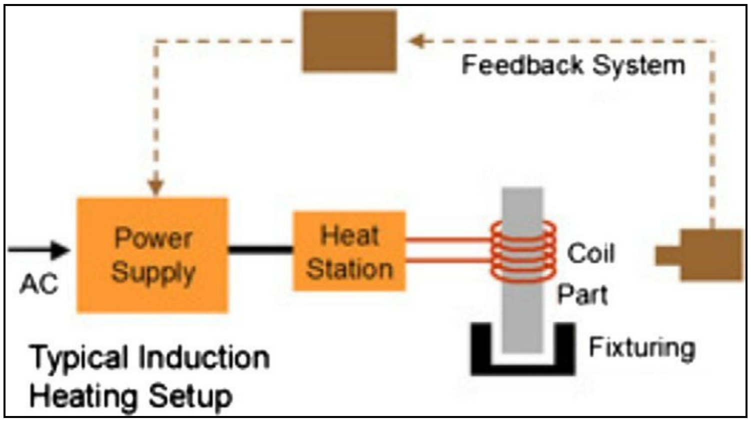

Figure 4: Induction Heating Setup

Chapter 2: Design

The main idea to design the new Jominy Hardenability test is mainly about making it a more safe operation. That's where the team started, what could make this long standing design more safe for people to be around and use? The best way to make the design as safe as we could make it is deciding to make it have in-situ heating of the alloy rod. In-situ heating refers to having the heating element inside the tester itself, instead of heating up the alloy rod in an oven first and then transferring it with a set of tongs over to the tester.

The whole idea of transferring the rod from an oven to the tester is not safe in a few ways. The fact that someone will be handing this red hot alloy bar a set of tiny tongs is the first issue, the tongs make it hard to hold the rod and the person runs the risk of dropping the rod. The next issue is having to fit the rod in a slot that is just slightly bigger than the rods diameter is so the lip can catch and hold it in place. When the rod is red hot and you are trying to fit it into place it can be stressful and the potential of dropping it and having to potentially heat it up again.

Now the question is: how do we do in-situ heating and still make it safe to operate? The first idea was to put an oven above where the rod was to slot into and have a removable door in the bottom of the oven that when the road was up to red hot temperatures, it would open and fall into place. This was a fine idea but still wasn't what the team was looking for. The combination of finding a suitable portable furnace along with structural concerns with space became too great to overcome. The next idea was to do induction heating. With an induction heater, there would be a rod in place like a normal Jominy tester but not yet heated. This enables the operator to prepare the specimen by simply placing it into the slot with their hand, then step back and push a button and let electricity do the rest by heating the specimen.

Induction heating allows the heating of the rod to red hot safely as there is not much human interaction with the rod until after the part has cooled down. The way the team has set up the tester, you put the alloy rod into the tester, start the controller and the induction process starts and heats the rod. An infrared laser positioned on the rod keeps track of the temperature and turns power off to the system to stop the heating of the rod. The inclusion of the infrared sensor is another way to keep the whole system safer by tracking the temperature reached by the specimen.

In order to make this tester come alive, we would need a tub to catch water from the cooling water umbrella and needed something to put everything on. Something that is sturdy and can hold all the weight of a tub with water along with all the electrical equipment that we would need.SInce this would be primarily used at the university, another goal was to make the structure mobile to use in classrooms and to move to various testing areas. Induction Tooling Inc. was our sponsor and support with anything and everything we needed for this project. In the early days in talks with them, we got an email from Bill Steuhr with a tub and aluminum cart on locking casters that he just had laying around and was going to get rid of. Figure 4 shows the stand and tub that Bill sent us and it is the perfect base and sturdiness for what the equipment we used needs.

Figure 5: Tub and aluminum stand on locking casters

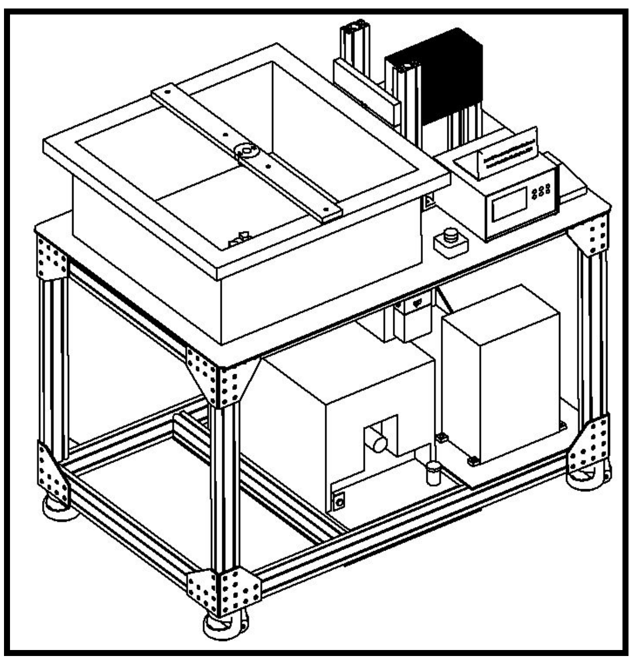

Figure 6: 3D view of Jominy Hardenability Tester

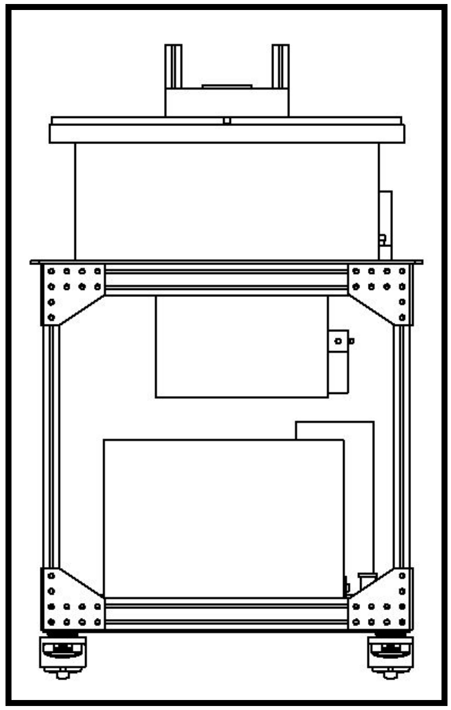

Figure 7: Front view of Jominy Hardenability Tester

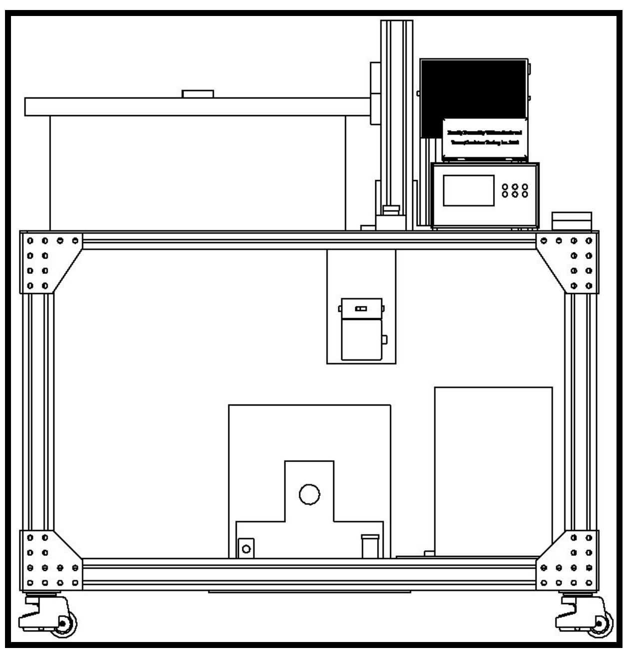

Figure 8: Side view of Jominy Hardenability Tester

Bill Steuhr and CEIA out of Twinsburg consulted with each other with what type of power system we would need. They decided on a system that included a power head, a water pump, work head, step down transformer, controller and anIR sensor all supplied by CEIA and Induction Tooling. The fact that these components are smaller than a few feet wide, long and tall, meant that it could easily fit into and on top of the cart that we were wanting to use.

The full design fit inside of a cart that was smaller than 40in x 40in x 60in, figures 6, 7 and 8 show the final design with all the power components that made it to the final design, it is a compact design and is more than ready to heat an alloy rod to red hot it under 3 minutes.

This design is an improvement over the old design in many ways, two of which are the important points our team wanted to make sure was followed through on. The first point was safety, the new design would limit the involvement of human dealing with a red hot rod with tongs, only to drop it on themselves or on the floor and have to start the process all over. The new design has in-situ heater via an induction coil that a human would just have to sit a rod in its slot and step back and start the controller, making it multitudes safer. Second is speed, with the old design, the oven in which the rod was heated up in would take roughly a half hour to heat up to red hot, and one drop of the rod on transfer to the tester would mean you'd have to start that process over. With the new design, you click a button on the controller and within minutes, your part is red hot and ready to cool, making the overall efficiency of the tester much greater and clear the better option.

Chapter 3: Discussion

One of the first steps in making and assembling the cart was designing and producing a coil that could heat our metal rod to the desired temperature of 1500℉. First, we calculated how much copper tubing would be needed to wrap around the metal rod. After we knew how much tubing we would need, we cut it and filled it with sand so that we could wrap the coil. The reason for filling it with sand was so that the copper tubing wouldn’t crack or fold, and with the sand inside, we had enough structural integrity to bend the tubing how we needed. We drilled a hole into one end of the copper tubing so that we could put a screw into it and attach it to a lathe. Figure 9 below shows the copper tubing being prepared to be wrapped on the lathe. Figure 10 shows how we screwed the tubing to the lathe to wrap it.

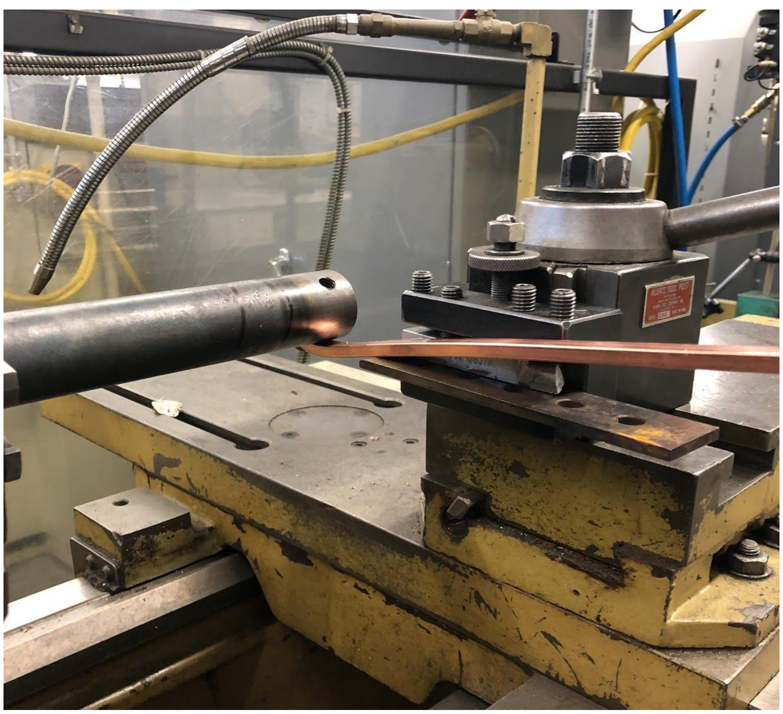

Figure 9: The copper tubing ready to wrap on the lathe

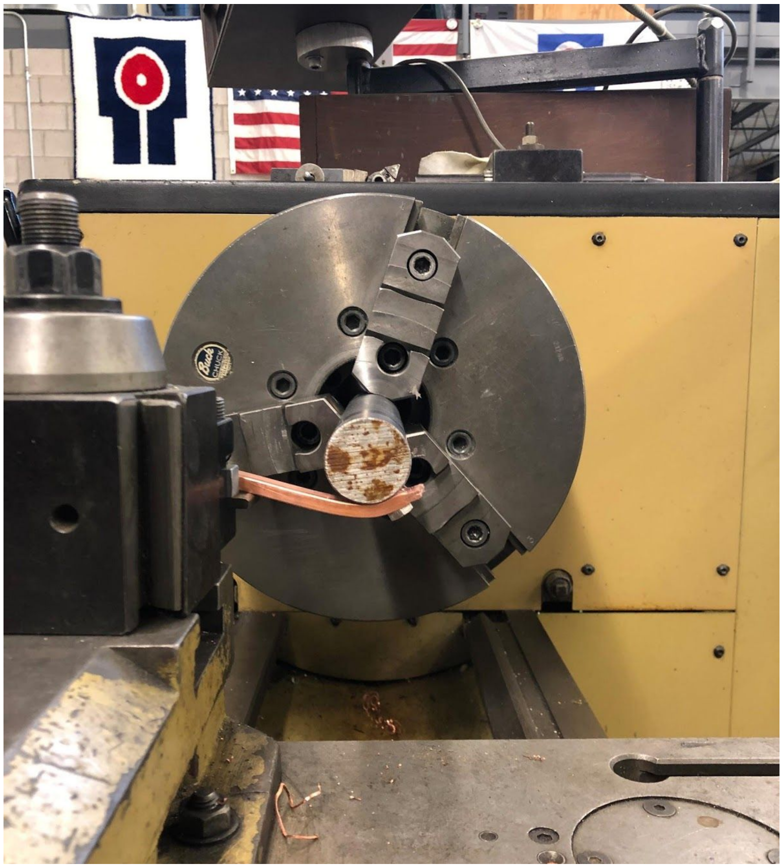

Figure 10: End view of the lathe and coil being wrapped

With a dull edge inserted where the cutting tool would be to guide the coil, we set the feed rate so that we would get the proper distance between turns. The amount of turns, diameter of the coil, and distance between the turns are all important in obtaining the correct inductance to heat the metal rod to the desired temperature. We manually turned the lathe so that it would turn slowly and would not deform the copper tubing any way we didn't want it to. With the sand being on the inside of the copper tubing, we didn't have to worry too much about it deforming. Figure 11 shows the finished coil wrapped on the lathe.

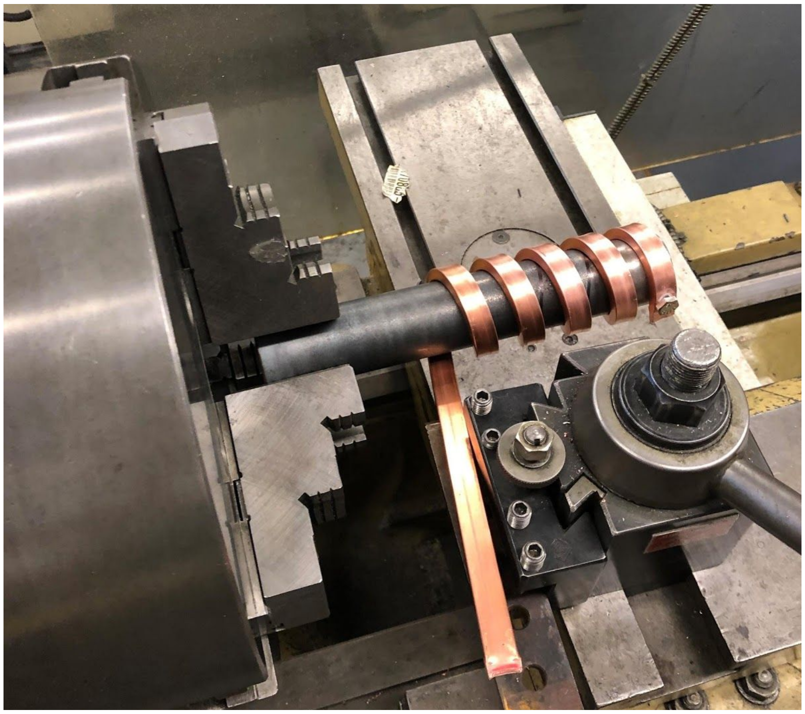

Figure 11: The finished coil wrapped on the lathe

After the coil was wrapped, we needed to machine a copper block so that we could connect the rectangular copper tubing to round copper tubing that would connect to the work head. Figure 12 shows us machining the copper block into a piece that would create a good connection between the round and rectangular copper tubing.

Figure 12: Machining a copper block for a strong connection

To join the round and rectangular tubing to the copper block, we used a torch to heat up the copper and brass filler rod to weld the pieces together. We coated the copper and brass filler rod in flux so that it would heat up and spread the filler rod uniformly throughout the gaps we needed filled. When the white flux starts to turn into more of a liquid substance, you know it is time to start applying the brass filler rod. Figure 9 shows us using the torch to heat up the copper and begin brazing the pieces together. In order to position the pieces how we wanted them to stay, we needed to get creative. We used several other different steel pieces such as the bar and 1-2-3 block shown in figure 13 to get the coil and blocks to sit perfectly so that we could braze them together and create a strong connection with no holes.

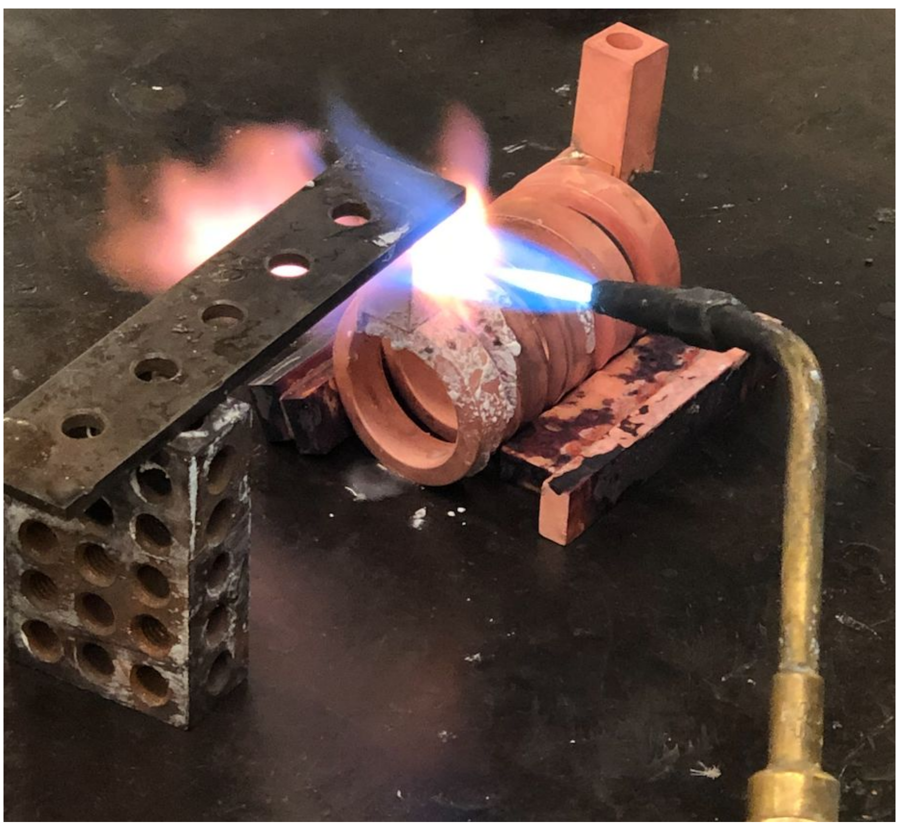

Figure 13: Brazing the machined copper block and tubing

After all of the copper pieces were brazed together, it was time to connect it to the work head and the cross beam going over the tub. Because the copper would be vibrating due to the amount of frequency going through it, we decided to drop down two non-conductive boards and braze two screws to the side of the coil to make it sturdy. Figure 14 shows the connection of the screws to the copper coil.

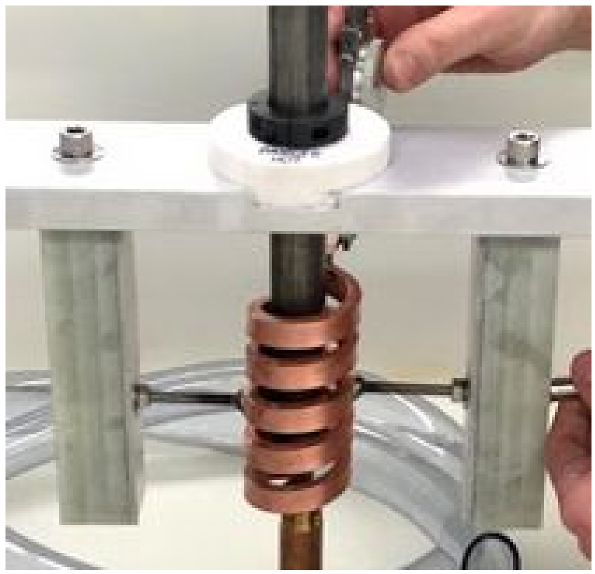

Figure 14: Copper coil brazed to the screws to keep it sturdy

Turn On Process

When turning on the Jominy Tester, strict and specific power on and power off instructions must be followed to allow for the accurate and safe operation of the tester. Induction heating is a very dangerous and effective tool and must be respected.

The first process is the power on. There are 4 steps to take when turning the Jominy tester on.

The first step when operating the Jominy is flipping the Main power Switch to the ON position. This will allow electricity from the room or building to be active on the cart. After flipping the switch to the On position, the cart has electricity and the next step can be followed. Figure 15 shows the location of the Main Power Switch.

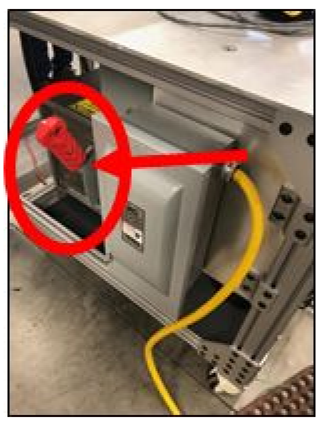

Figure 15

The second step when powering on the tester is turning on the power supply. The power from the main switch will activate power anywhere on the cart. By turning the power supply pictured in figure 16, the controller and work head for the induction coil can now be powered.

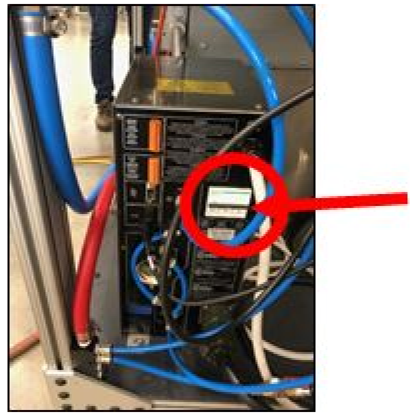

Figure 16

The third step is turning on the water pump. The purpose of the water pump is to supply cooling to the induction coils and workhead due to the large amount of heat created. This can be seen in figure 17.

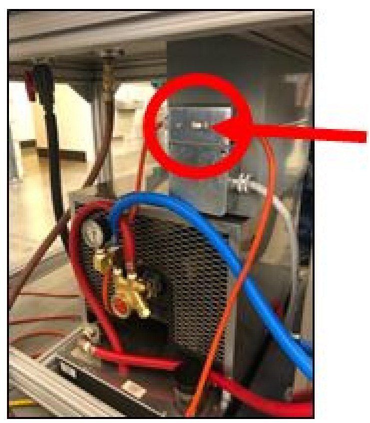

Figure 17

The final step when turning on the tester is turning on the controller. The controller is the programmable brains of the induction process that allows the user to customize the test and what the induction coils do. The controller also tracks and graphs the temperature increase and decrease while the jominy test is being conducted. The controller can be seen in Figure 18.

Figure 18

Power Off Process

With the power on instructions discussed, the next step after the test is conducted is to power off the unit. The power off instructions are specified further in the appendices with Power On and Power Off instructional guide.

The first step in powering Off the tester is to turn off the controller. Turning off the controller will cut off power to the workhead and to the coils. This can be seen in Figure 19.

Figure 18

The second step is to turn off the water pump. It is important that you wait 1-2 min before turning off the water pump to allow the water to be cycled before turning off. This is shown in Figure 20.

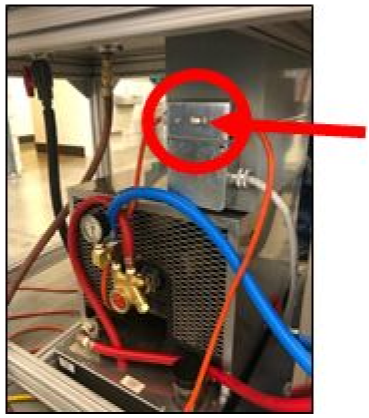

Figure 20

The third step is turning off the power supply. This will shut completely off the power to the induction portion of the tester. This is shown in Figure 21.

Figure 21

The last step to turning off the Jominy Tester is Flipping OFF the main power. This will completely shut the cart down from any power. This can be seen in Figure 22.

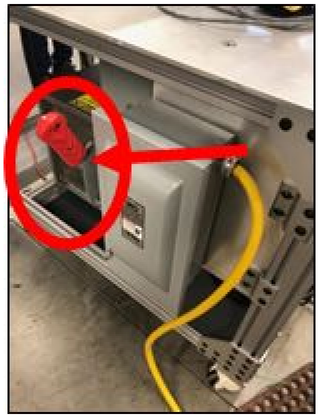

Figure 22

These Instructions are very important to be followed for safe operation. Any deviation could cause damage to the machines and a potentially unsafe environment.

Calculations

$$Micro\ Henry = \frac{N^2 * D^2}{18D + 40L} \qquad \textbf{(1)}$$

Equation 1 is used to calculate the micro henrys. There are one million microhenrys in a henry. In this equation N is the number of turns, D is the diameter of the coil, and L is the length of the coil.

$$Length = N * \sqrt{(\pi * D)^2 + P^2} \qquad \textbf{(2)}$$

The equation 2 is used to find the length of the coil. N is the number of turns, D is the diameter and P is the pitch.

Warnings when operating

There are several precautions to take before being around and operating the new Jominy Hardenability Tester. One huge precaution to be aware of is if you have a pacemaker, the magnetic field from the induced current could cause the pacemaker to not work as reliably and be considered an important health risk. Another risk that needs to be careful of before use is wearing jewelry, specifically fully closed rings, as in a wedding band or a similar type of ring that goes all the way around a finger, this is because the ring could melt or you could touch a portion the tester that has power running through it and you could be severely electrocuted.

Another huge precaution to take is making sure all the electricity is turned off after using the machine. You don’t want an unauthorized operator to come up to the machine after your team has left and electrocuting themselves. It’s also important that when the machine is running just to not touch it at all. The powerhead has a red LED light on the front of it that turns on when current is flowing and off when current is flowing. So if the red light is on do not touch any part of the cart. If the red light is off, make sure all power levers and switches are turned off before proceeding to make contact with any part of the cart.

There are some controller warnings that should be make clear before using, these errors will come up on the controller prior, during and after use, and there are more than these but these will be more frequent during normal use:

Error Number	Description
A3	Pressure may be too low
A4	Coil length is too small
A5	Coil length is too big
A10	Voltage is too low
A14	Temperature time out

Chapter 4: Conclusions

Working on this project has been a total honor to be a part of. We were able to meet new people out in industry as well as learn a new concept. We were able to meet with two different owners of companies known worldwide.

The first person we met with was Joe Powell. He is the owner of Akron steel treating, just down the street from campus. After meeting with him he got us in contact with William Steuhr at induction tooling. William is the owner and founder of Induction tooling.

If we hadn't met either of these wonderful gentlemen, our project would not be the same as what it is today. William dug deep into his resources to help us out and really bring the Jominy hardenability tester into the future.

All in all we were able to create a real world, working, induction heating Jominy hardenability tester. As far as we are aware this is the only one in existance and we were the first to accomplish this feat.

In the brief time that we were able to work with the tester, we were able to prove that the concept works.Our tester involves all current day products that are made by Ceia. The Ceia products are the work head, the power supply, the infrared camera and the module that runs the programs. All of these products were donated to us so they will belong to the project forever.

The coils were hand built by ourselves and the team at Induction tooling. While making the coils we were able to try brazing. Brazing is a process very similar to welding but it is used on copper products. To braze there is an open flame torch used to heat up the copper and then solder is applied. The solder bonds the two pieces together and creates a fully sealed bond.

The cart was made by William years ago and was going to end up getting tossed. The tub was another piece that was in the scrap bin that was very close to what we wanted. So we were able to repurpose the cart and the tub for years to come.

Our group also made all of the green non-conductive board pieces and the Aluminum bar that holds the sample using a mill. Once all of the parts were machined or made everything was able to be bolted together and set up for testing. During the testing phase we had to change our coil a couple of times, but eventually came to a coil that should work as we intend for the variety of materials we could test.

Thankfully before all of the Covid issues arose, we were able to invite Bill to bring the tester down to Akron. The tester made its way to the lab and then we were able to rebuild the cart and bolt everything back down.

Unfortunately, we were unable to test it in our lab before we had to leave campus. The tester can not be turned on until Bill comes back down to akron to review that everything is still hooked up correctly.

Another step that needs to be completed is setting the water pressure that creates the correct fountain. This process will take two people to do. Another side note is that this process is to be done with the specimen out of the way. One will have to sit there and use a ruler to measure the height of the water fountain. The goal is to get the umbrella to sit 2 inches above the top of the pipe.

The other person will adjust the valve to try to get the umbrella to the correct height. Once the height is set correctly that valve should never need to be touched again. We added an extra valve so that one sets the water to the correct pressure and then the valve off the wall can be used to just simply turn the water on and off.

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Appendices

Drawings

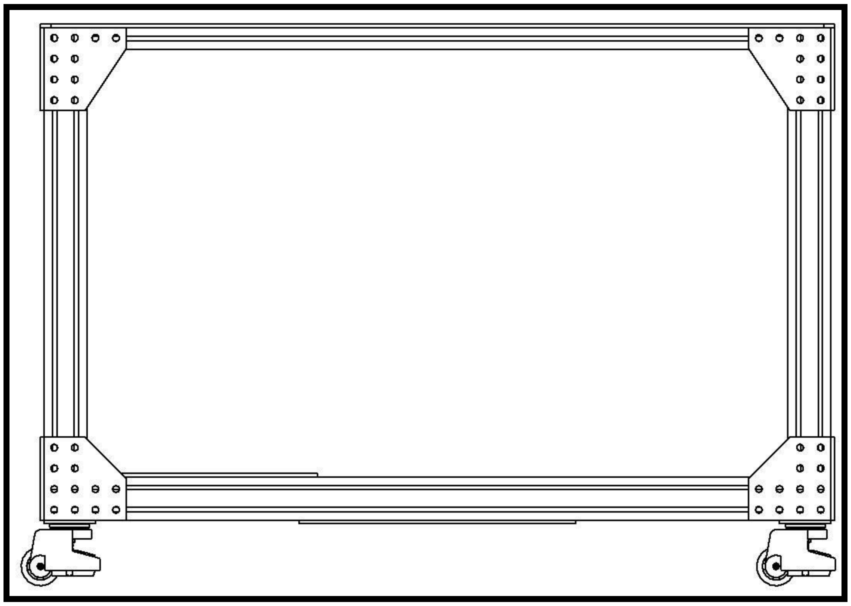


Figure 22: Side view of cart only

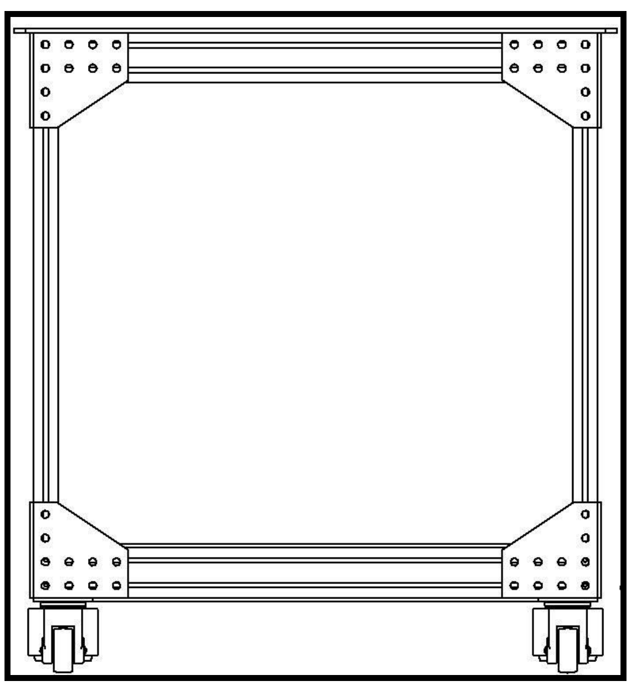


Figure 23: Front view of cart only

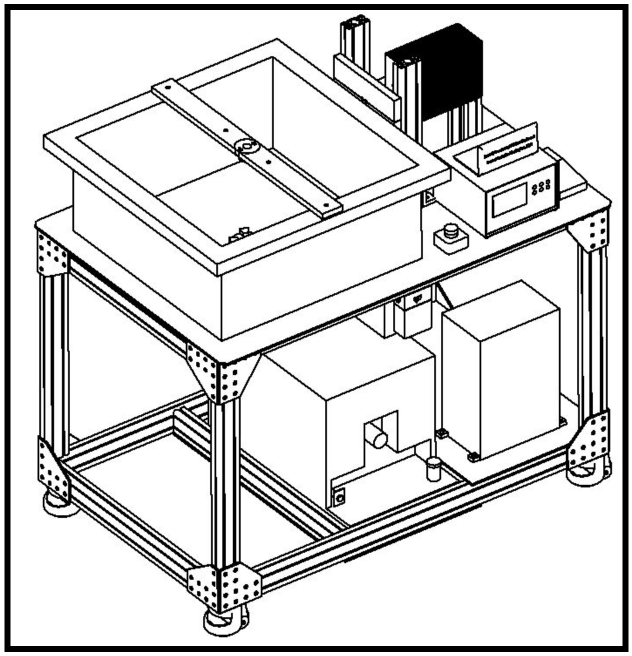


Figure 24: 3D view of Jominy Hardenability Tester

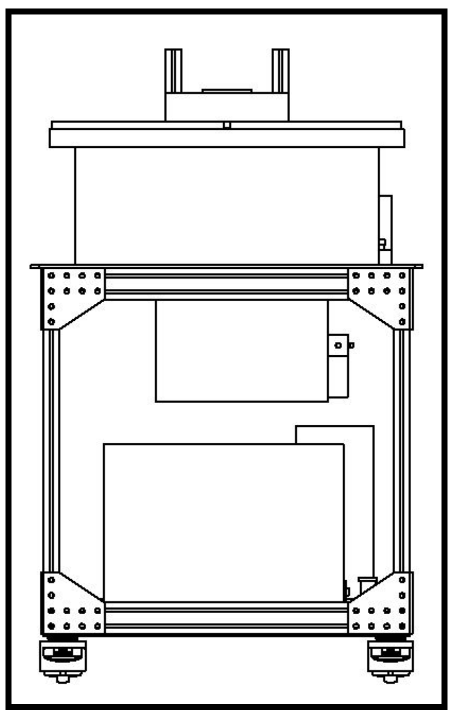


Figure 25: Front view of Jominy Hardenability Tester

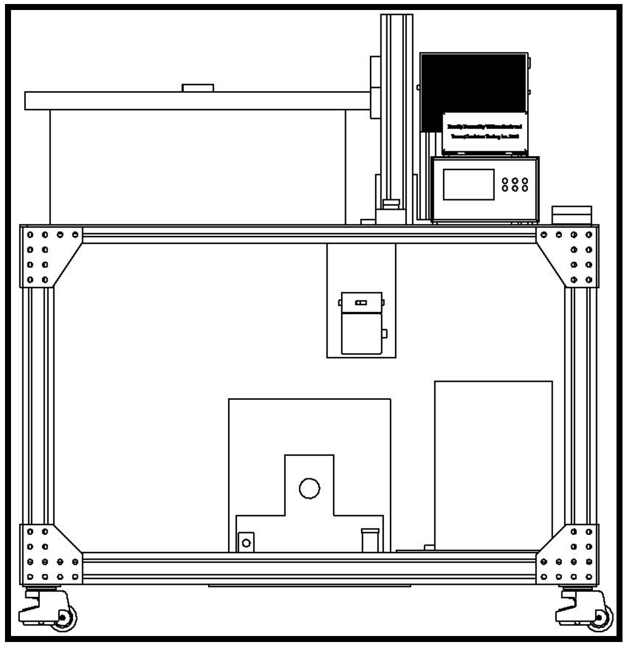
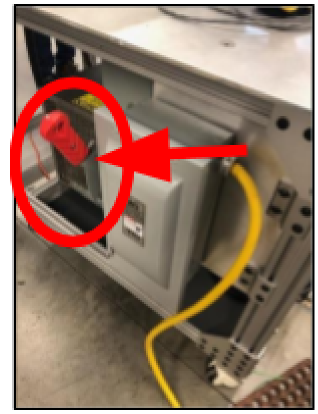


Figure 26: Side view of Jominy Hardenability Tester

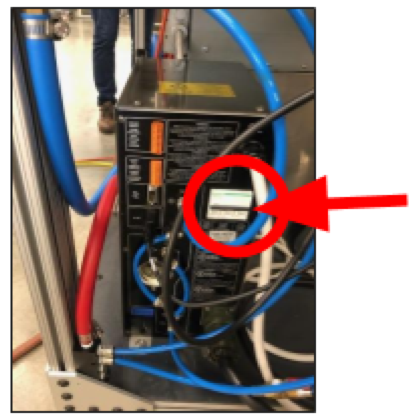
POWER ON INSTRUCTIONS

PROCEDURE

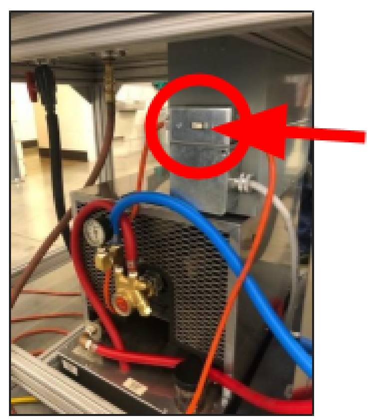
1) Flip Main Power Switch On



2) Turn on Power Supply



3) Turn on Water Pump



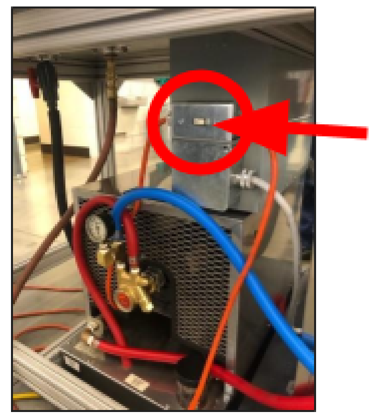
4) Turn on Controller

POWER OFF INSTRUCTIONS

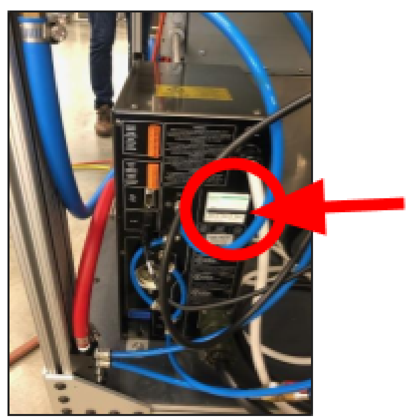
PROCEDURE

1) Turn Off Controller

2) Wait 1-2 min, Turn off water Pump



3) Turn Off Power Supply



4) Flip Off Main Power