Construction of a Variable Compression Engine for the Classroom

A Major Qualifying Project

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In Mechanical Engineering

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Abstract

The purpose of this major qualifying project (MQP) is to design and manufacture an engine head that allows for the variation of the compression ratio for a lawnmower engine. This engine will be used as a classroom demonstration tool for the Worcester Polytechnic Institute (WPI) Mechanical Engineering Department. The engine must be able to run safely in a classroom setting and have the ability to adjust the compression ratio between 2:1 and 7:1 while the engine is running and able to withstand sub-optimal operating conditions. Other requirements include easy transportation to and from the classroom, and the ability to easily adjust the compression ratio. The design focuses on modifying a lawnmower engine and replacing the cylinder head with a movable piston mechanism that allows the user to vary the head volume, while the engine is running; thus, changing the compression ratio.

The design of the engine head mechanism was completed, and the majority of the parts were manufactured almost entirely in WPI's Washburn Shops out of cast iron with the exception of a few parts being purchased on McMaster-Carr. The mechanism consists of an outer housing, a plunger, and an Acme rod subassembly that allows the plunger to be raised and lowered. Moving the plunger up and down changes the volume above the engine piston and thus the compression ratio. The team was able to manufacture the entirety of the engine head mechanism except for the plunger which needs only one small modification to complete.

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Introduction

The internal combustion engine is a type of heat engine that many commercial vehicles are equipped with today. It converts chemical energy into mechanical energy through the combustion of an air and fuel mixture in the piston chamber. In 1876, German inventor Nikolaus Otto developed the first four-stroke internal combustion engine that burned fuel within the enclosed piston chamber. Otto started the development of his engine by improving upon the gas-powered engine developed by Belgian inventor, Etienne Lenoir, which tended to be noisy, use a large amount of gas, and produce a large amount of heat. Otto's engine was developed with a four-stroke process (intake, compression, power, and exhaust) that ran on liquid fuel. Otto discovered that the use of one piston per chamber made the engine much more efficient than the gas-powered engine. Demand for the engine began to rise due to its efficiency and ability to run relatively quieter than the engines previously in the market [36].

The premise of this project was the creation of a variable compression internal combustion engine that allows the user to alter the compression ratio while the engine is running to demonstrate how compression ratio affects engine performance. This was done by creating a mechanism that replaces the head of a lawnmower engine. The mechanism allows the user to raise and lower a plunger above the piston, which changes the volume above the piston and thus the compression ratio. The mechanism along with the lawnmower engine will be used to demonstrate the effects of different compression ratios on a running engine.

1.0 Background

1.1 Internal Combustion Engine Overview

An internal combustion engine operates by transforming energy created by burning an air-fuel mixture into mechanical work. It is called an internal combustion engine because the ignition and combustion of the fuel take place inside the engine, in a combustion chamber [26]. The engine is primarily made up of a cylinder and a moving piston. When the air-fuel mixture ignites inside the cylinder, the gasses expand pushing the piston down and turning the crankshaft. By turning the crankshaft, the engine can provide motion to the device the engine is being used to run [29]. These could include the wheels on a car, the propeller on an airplane, or the blade on a lawnmower. The two main types of internal combustion engines are gasoline and diesel engines. The key difference between the two is how the fuel is ignited inside the combustion chamber. A gasoline engine, seen in Figure 1, uses a spark plug to ignite the fuel, and a diesel engine ignites the fuel by compressing the mixture until it combusts [29].

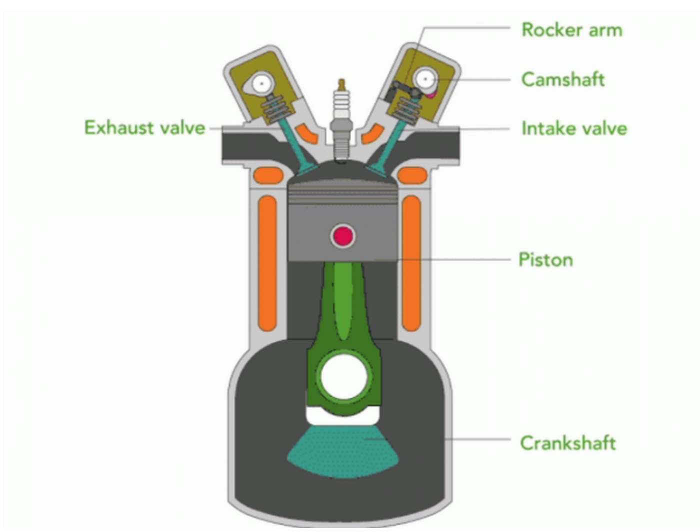

Figure 1: Internal Combustion Engine Parts [28]

1.2 Four Stroke Engine

Most internal combustion engines are four-stroke engines. This refers to the number of piston strokes required to complete one engine cycle [28].

The four strokes include the intake stroke, the compression stroke, the power stroke, and the exhaust stroke [25].

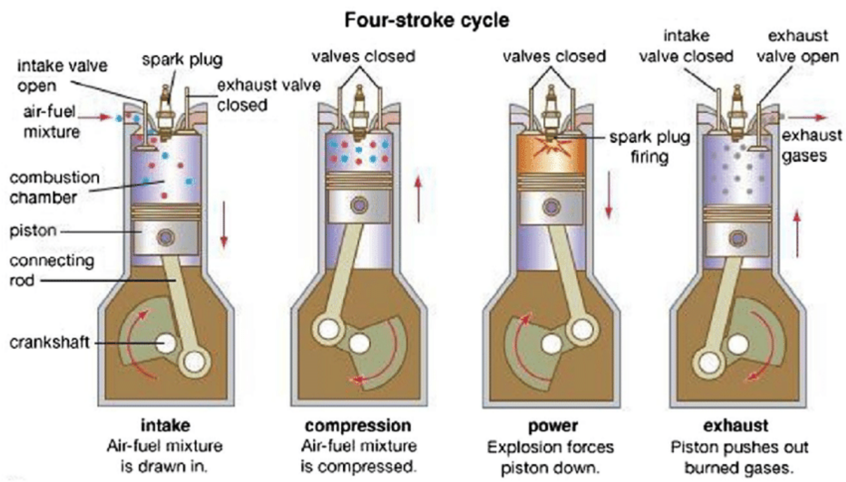

Figure 2: Four-Strokes of an Internal Combustion Engine [24]

During the intake stroke, the piston moves from top dead center to bottom dead center. As the cylinder moves down, a vacuum is created above the cylinder. Simultaneously the inlet valve opens with the timing of the piston motion via a camshaft. The vaporized gasoline from the carburetor or fuel injection enters the chamber and mixes with the air entering through the intake valve. Once the cylinder passes bottom dead center, the intake valve closes, and the intake process ends [33]. Typically, the compression ratio is approximately 9:1 in gasoline spark ignition engines [33] and 15:1 in diesel engines [47].

During the compression stroke, the piston moves from bottom dead center to top dead center compressing the mixture of air and vaporized gasoline. The temperature and pressure of the contents in the chamber begin to increase [23].

During the power/ combustion stroke, both intake and exhaust valves are closed. The piston ascends and returns to top dead center, and an electric current triggers the spark plug which ignites the compressed gas in the chamber. The gas expands, and pressure and temperature increase rapidly in the combustion chamber. The resulting pressure pushes the piston down with several tons of force.

During the exhaust stroke, the inlet valve remains closed whilst the exhaust valve opens. The moving piston pushes the burned fumes through the now open exhaust port and another intake stroke starts again.

1.3 Fuel Mixing

A crucial part of efficient power production for engines has to do with the intake of the optimal fuel to air mixture. This is important because the correct fuel-air mixture is responsible for igniting during the combustion stroke, expanding, and ultimately moving the drive shaft. The ideal fuel ratio is 14.7 parts air to 1 part fuel. This perfect mixture will result in all the oxygen and all the fuel being burned since the amount of air introduced sets the amount of fuel needed. This ideal fuel mixture is known as the stoichiometric ratio. If there is too much gas present in the mixture, you may notice reduced engine efficiency and worse fuel economy but can generate more power and burn cooler. This mixture is known as a rich fuel mixture and is common and not necessarily detrimental to the engine. If too little gas is present, then the mixture possibly won't ignite and the engine won't produce its full power resulting in poor operation which could lead to engine damage possibly burning valves, this is known as a lean mixture [43].

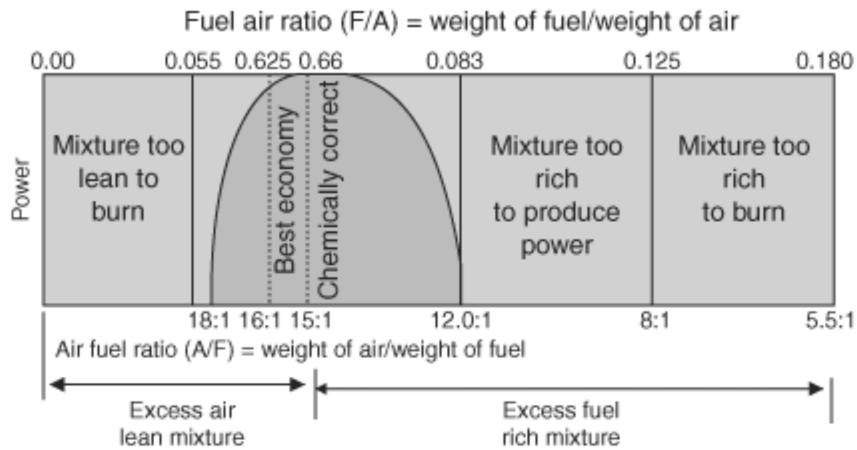

Figure 3: Fuel Mixture Graph Fuel Mixture Graph [19]

The two main delivery systems responsible for introducing fuel and air into an engine are a fuel injector and the carburetor. Fuel injection was first developed by Herbert Akroyd Stuart; he used a pump to pressurize the fuel. This invention was adapted for use in diesel engines by Bosch and Cummins. It was Jonas Hasselman in 1925 that created the Hasselman engine which was the first engine to use modern fuel injection in a petrol engine [17]. Electronic fuel injection consists of a set of fuel injectors, an oxygen sensor, and a fuel pump with pressure regulation. A computer then controls how much atomized fuel is delivered to the cylinders resulting in better performance and better fuel mileage.

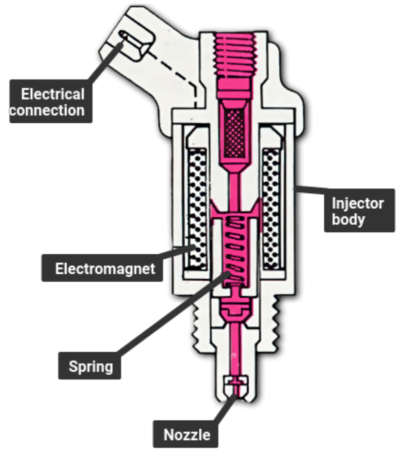

Figure 4: Diagram of a Fuel Injector [5]

The first carburetor was invented in 1826 by Samuel Moey, however, the float-based carburetor was developed by Wilhelm Maybach and Gottlieb Daimler in 1885 [6]. Carburetors are most common due to their simplicity and effective fuel induction methods. A carburetor uses a Venturi Tube which decreases air pressure creating a vacuum, this is known as the Vacuum Venturi Effect [3]. This vacuum force pulls fuel into the carburetor where it is mixed with air and is sucked into the engine during the intake stroke. A carburetor has two valves, the choke which regulates the amount of air mixing with the fuel which can create leaner mixtures, and the throttle valve which regulates the flow of the air-fuel mixture to the engine. Fuel is introduced through small jets which help to achieve max efficiency and performance. On the bottom of the carburetor, there is a float-feed chamber that stores a small amount of fuel that feeds to the engine. When its level drops too low, the float opens a valve, and the fuel is replenished [3]. Carburetors are pretty simple to clean and rebuild whereas fixing a fuel injection system requires professional intervention or even an expensive piece of test equipment. Due to these reasons, we decided to use a carburetor to supply the air-fuel mixture for our project engine.

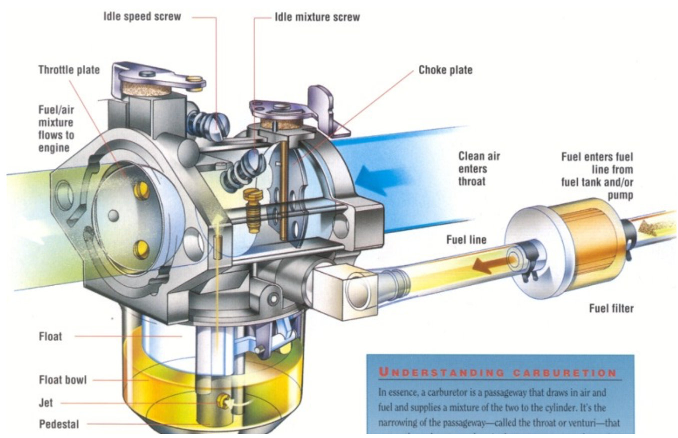

Figure 5: Diagram of Carburetor [9]

1.4 Ignition Timing

Ignition timing can have a major effect on the performance of an engine. Ideally, the spark should be timed to produce maximum cylinder pressure just after top dead center. As engine speed changes, the crank angle of the spark must also change to produce this result. Load and mixture can also affect engine timing. By changing the ignition timing, it is possible to increase the efficiency and power production of an engine. This is done by either advancing or retarding the ignition timing. If the spark plug fires too soon or too late during the compression stroke, damage to the engine can occur over time. A range of factors can influence the ignition timing including the condition of the spark plugs, the temperature of the engine, and the intake pressure. Modifications or changes to an engine can also require subsequent changes to the ignition timing settings [2]. For our variable compression ration engine, it is desired to change compression and timing independently so that the effect of each is experienced separately.

Ignition timing is measured in degrees of a crankshaft rotation before top dead center. For an engine to operate efficiently, the spark plugs need to fire at the right time, which can be achieved by advancing or retarding the timing of the engine. Ignition timing advancement refers to the spark plugs firing earlier in the compression stroke, farther from the top dead center of the piston. This can allow more time to ignite the fuel mixture in the cylinder resulting in an increase in horsepower. Ignition timing should be set so that maximum cylinder pressure is achieved right after top dead center (TDC). Too early and power will be wasted as the engine must work against itself and too late, the engine will be unable to make use of the full energy of the expanding charge. Ideal spark timing is therefore dependent on engine speed. Some advance is required due to the ignition delay before the flame begins to propagate [18].

1.5 Knocking

Knocking is the result of abnormal combustion, which results in pressure rising too rapidly and reaching its maximum pressure too early. When there is the correct balance of air and fuel in a cylinder, the fuel will burn in small, regulated pockets instead of all at once. Engine knock can produce an annoying noise and potentially damage your engine's cylinder walls and piston. Many things can cause engine knock, some of which include faulty spark plugs, low octane fuel, and carbon deposits in the engine [44].

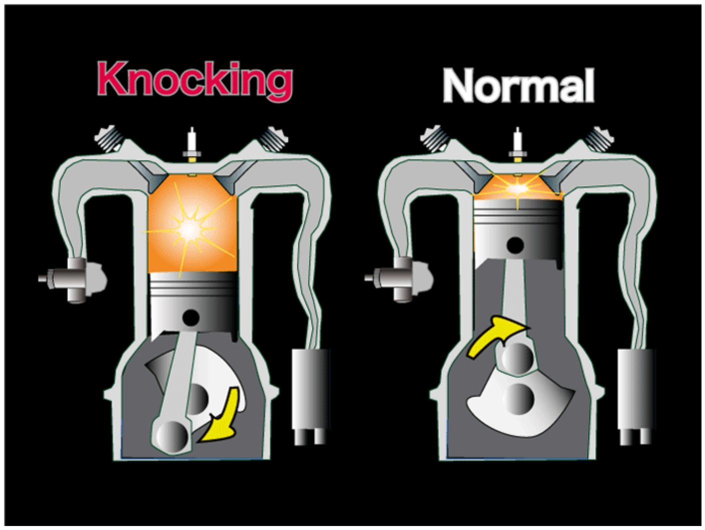

Figure 6: Knocking Vs. Normal Performance [30]

1.6 Compression Ratio

An engine's compression ratio is defined as the ratio of the volume of the cylinder and the headspace at the bottom of the stroke to the volume of the headspace when the piston is at the top of its stroke. A piston at its lowest point is called bottom dead center which is where the cylinders volume is the greatest. When the piston is at the highest point within the cylinder, that's called top dead center and that's where cylinder volume is smallest [15] in layman's terms, the compression ratio is the ratio of the volume above the piston at the bottom of the stroke and the top.

If an engine has a high compression ratio, it means that a given volume of air and fuel in the cylinder is being squeezed into a much smaller space than an engine with a lower compression ratio. The compression ratio can be calculated with the equations which can be seen in figure 7.

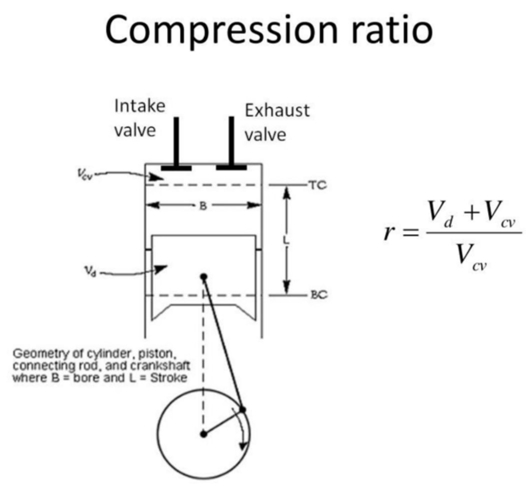

Figure 7: Compression Ratio Equations [11]

1.7 Variable Compression Ratio Engines

While this project focuses on creating a variable compression ratio (VCR) engine to be used as a classroom demonstration, many existing VCR engines are made to increase fuel efficiency in the automobile industry. Several automobile companies are using a multi-link system to change the stroke length of the piston in order to vary the compression ratio. This process will require a variable timing control system that can control the intake and exhaust valve timings to reduce any excessive loss of air out of the engine that can lower the power output [29]. At low loads, when not much power is needed, the VCR engine operates at a low compression ratio, which results in less fuel consumption. When more power is needed the compression ratio is increased to save fuel [15]. A VCR engine allows the engine to operate at the optimum compression ratio to maintain fuel efficiency when operating under different loads.

2.0 Methodology

Based on the background research conducted, the team began to design and manufacture the engine head mechanism for the lawnmower engine. The following objectives describe the steps taken to complete this project.

1. Rebuilt/Repair Lawn Mower Engine
2. Design and Specifications
3. Manufacturing

2.1 Rebuilt/Repair Lawn Mower Engine

The first step taken was to repair and rebuild a broken lawnmower engine. This was done to help gain a hands-on understanding of how an internal combustion engine works. The engine available for the team to use was a Tecumseh LV195EA [40] lawnmower engine. This engine was selected due to its flat head design which means the valves are located to the side of the piston instead of above it, which is required for the overhead plunger mechanism we designed to vary the compression ratio.

Figure 8: Engine Before Rebuild and Cleaning

The process was started by completely disassembling and cleaning every component of the engine. To clean the components the team started by removing all the dirt from the outside of the engine with brushes. Once the exterior was cleaned, we proceeded with disassembling the engine and cleaning the interior components. Once the outer casing had been taken apart the team realized that the entire engine had been flooded with oil, most likely because of being tipped over. This meant that almost every component had to be degreased and cleaned before reassembling it. To do this, we needed to disassemble every single component and mechanism inside the engine. This included the piston, crankshaft, flywheel, valves, exhaust, carburetor, and others. By disassembling every component, we were not only able to clean it more effectively, but it also gave us a much better understanding of how an engine operated. For example, being able to see the valves move up and down in sequence while moving the piston was extremely beneficial in understanding how each of the four strokes worked. After disassembling the engine, we began cleaning the components with both degreaser and brake cleaner. WD-40 was also used to help remove rust from some of the components.

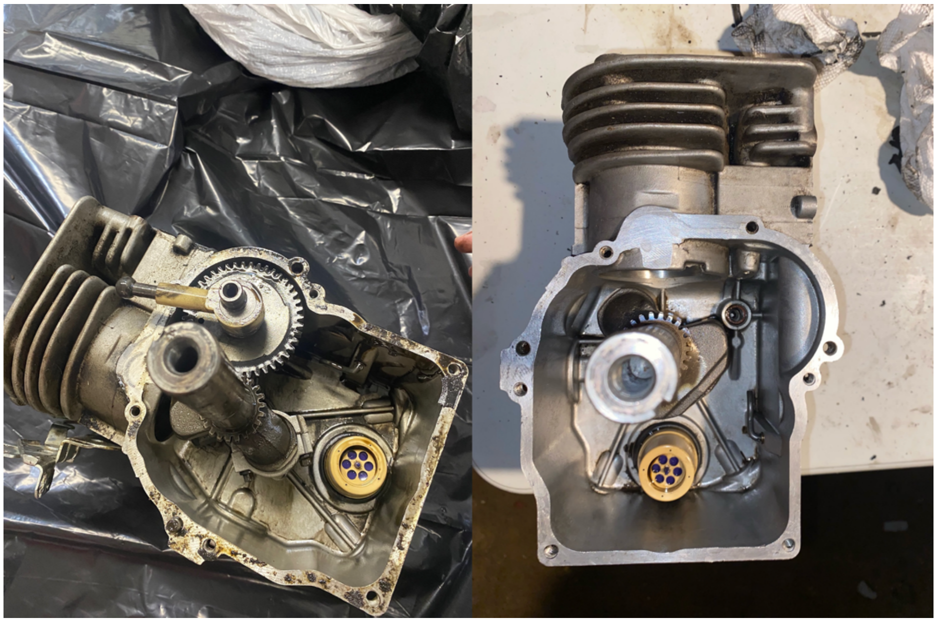

Figure 9: Inside of Engine During Cleaning Process

In addition to cleaning the components, the team also needed to replace and repair some parts of the engine. One of these was a broken piston ring that needed to be replaced. Replacement parts for this engine are not easy to come by, so the team sought out assistance from a local lawnmower repair shop. The shop did not have a spare ring, but they were able to provide the part number. The part number allowed us to find the exact part we needed on the manufacturer's website and purchase a spare set of piston rings. In addition to replacing the broken piston ring, the team also needed to replace the filters in the carburetor, which has been flooded with oil. The seals between the engine head and casing also had to be replaced. To do this, we purchased a sheet of gasket material and cut out the shape of the seal by hand with an X-Acto knife which can be seen in figure 10. After cleaning and replacing the damaged components, the team reassembled the engine.

Figure 10: Custom Made Engine Head Seal Figure

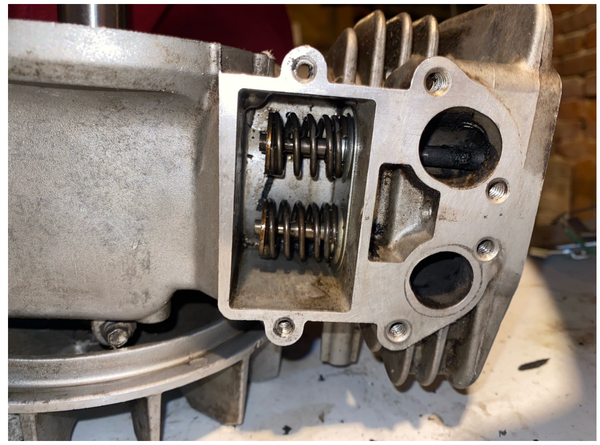

Figure 11: Intake and Exhaust Valve

2.2 Design and Specifications

2.2.1 Design Constraints

There were several design constraints that the team had to consider when designing the engine head mechanism. The first was that the team wanted to modify a lawnmower engine instead of creating a complete engine from scratch, which was not feasible given our timeframe. Because the mechanism and the lawnmower engine would be used as a demonstration tool, it had to be safe to operate while the engine was running. The biggest challenge in the design of the mechanism was accounting for all the engine's functions, and to ensure that changing the compression ratio would not affect any of the other parameters, especially valve and ignition timing. These constraints include space for the spark plug, keeping head geometry intact, accounting for valve clearance, and achieving the desired compression ratios. The team also considered that the engine and the mechanism must be able to withstand everyday wear and cannot leak under operation. All these major design constraints had to be manufacturable with available resources at WPI.

2.2.2 Design Process Overview

There are several methods that the team considered to vary the compression ratio of an engine. One is to adjust the stroke of the piston by moving the cylinder head, the crankshaft axis or using a linkage system. Figure 12, below, shows a VCR engine that operates by using a linkage to move the crankshaft and alter the piston stroke [35]. Adjusting the stroke of the engine had two major drawbacks. The first was that using this method would require either significant modifications to the lawnmower engine or the creation of a completely new engine. The second was that altering the stroke also required the valve and spark plug timing to be changed. One of our design constraints was the ability to alter compression ratio independently of ignition and valve timing so this method was not chosen.

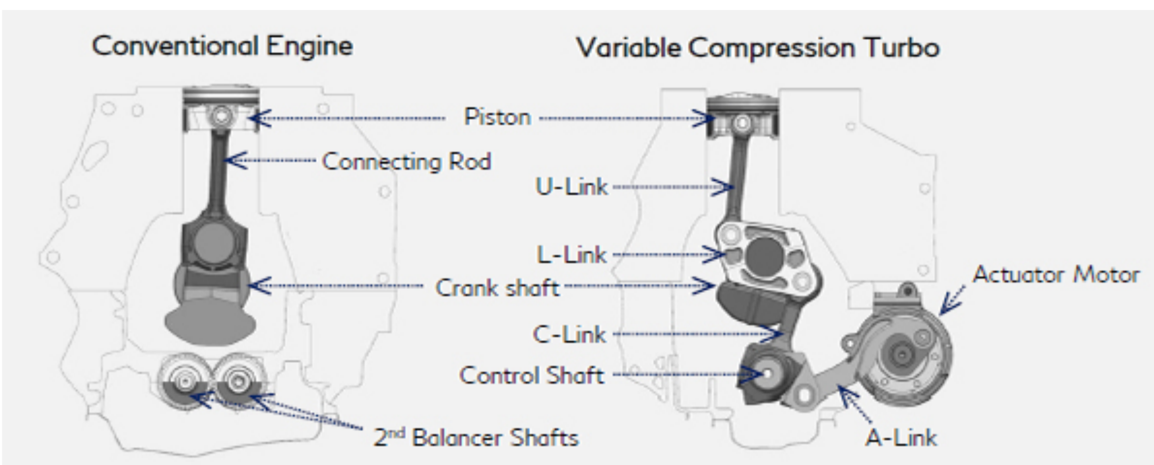

Figure 12: Conventional Engine Vs. Variable Compression Engine [42]

Another method of varying the compression ratio is to vary the head volume above the piston. This method was advantageous because it did not require changing the timing of the engine. This could be done by changing the height of the cylinder or by using a plunger mechanism to change the volume above the piston. The team first considered varying the head volume by lengthening and shortening the cylinder. This method was used by a previous MQP that designed an entire VCR engine from scratch but did not manufacture it [21]. Our team looked at this design but noticed that changing the height of the cylinder had a major drawback. Lengthening or shortening the cylinder would also require changing the height of the valves. This would require designing an additional mechanism to change the height of the valve stems, which would significantly increase the complexity of the design and the number of parts needed to be machined. The team determined that this was not feasible to complete within our time constraints.

The team built upon the method of varying the head volume and came up with an original method to vary the compression ratio. Our design alters the head volume by raising and lowering a plunger above the piston. This design had two major advantages. It did not require changing the ignition or valve timing or changing the valve height. This made our design significantly simpler than the methods discussed above.

2.2.3 Design Overview

The chosen design is capable of varying the compression ratio from 2:1 to 7:1 without changing valve or ignition timing. The final assembly and section view is shown below in Figures 13 and 14.

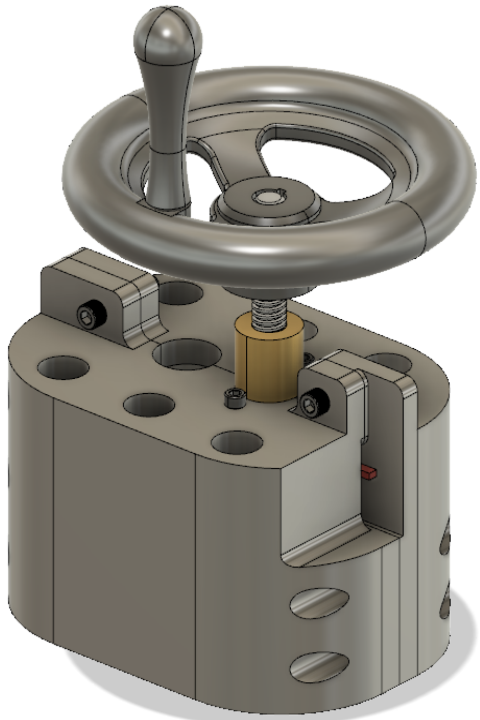

Figure 13: Engine Housing Mechanism

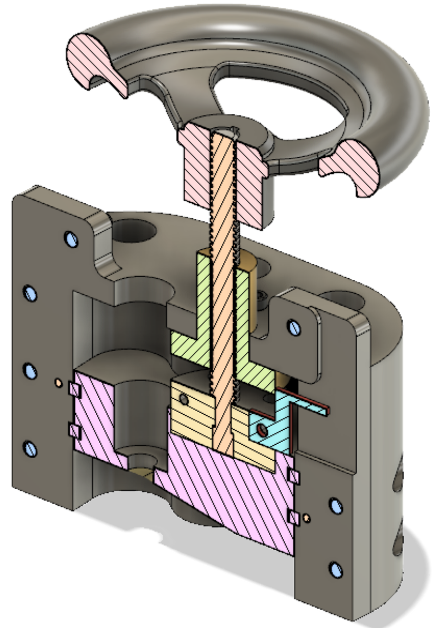

Figure 14: Section View of Engine Housing

The mechanism consists of six main components, a hand wheel, a steel precision Acme threaded rod, a bronze precision Acme flange nut, a machined cast iron housing, a machined cast iron collet, and a machined cast iron plunger, components are labeled below in Figure 15. The mechanism is held together using various bolts and pins that are all detailed in our bill of materials in Appendix C.

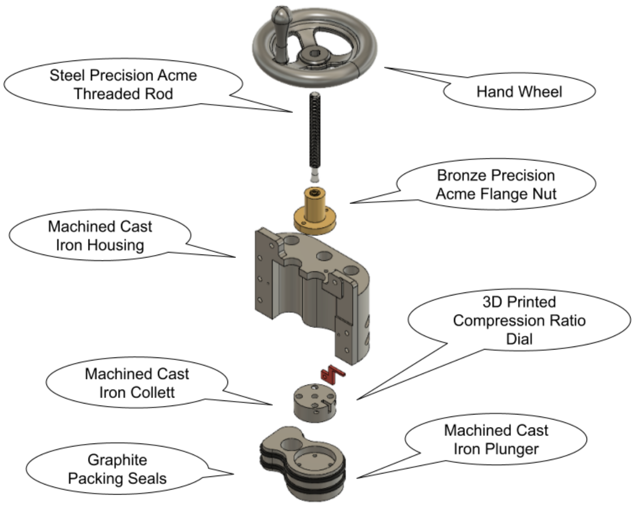

Figure 15: Labeled Mechanism Components

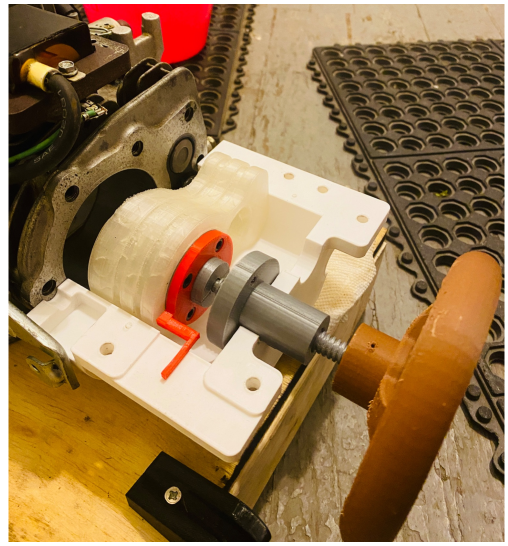

Figure 16: 3D Printed Prototype Mounted to Head of Engine

The mechanism is bolted to the head of the lawnmower engine shown in Figure 16. Since a flat head engine is being used, the plunger acts as the new head. The plunger is able to move up and down by using an Acme threaded rod and precision flange nut. Moving the plunger inside the housing alters the head volume above the piston and thus results in a variable compression ratio. The threaded rod is machined and attached to the plunger using a collet which allows the threaded rod to free spin in the plunger. A 3D printed dial is attached to the collet which allows the user to read what the compression ratio is at a given position.

2.2.4 Housing

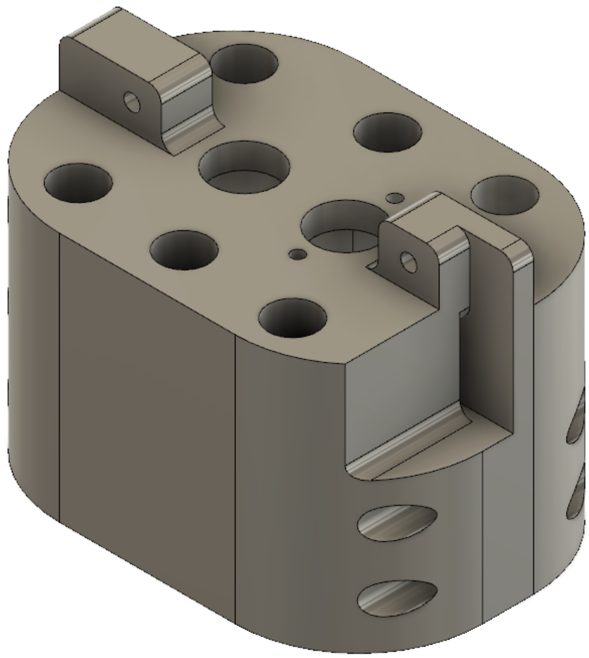

Figure 17: Engine Head Mechanism Housing

The housing is the most important component of the mechanism, this is because in addition to holding the plunger and the other main components it also must withstand high temperature and pressure resulting from engine operating conditions. Machined out of cast iron as mentioned in the 2.3.2 Material choice section, has good thermal properties. The challenge when designing the housing was how many different components had to fit in a small area. We had to utilize pre-existing bolt holes on the engine head which made the process of fitting everything challenging. As seen in Figure 18 the inner plunger pocket has a small wall thickness between the bolt holes about 0.100 in. This unfortunately was an unavoidable consequence of altering an existing engine.

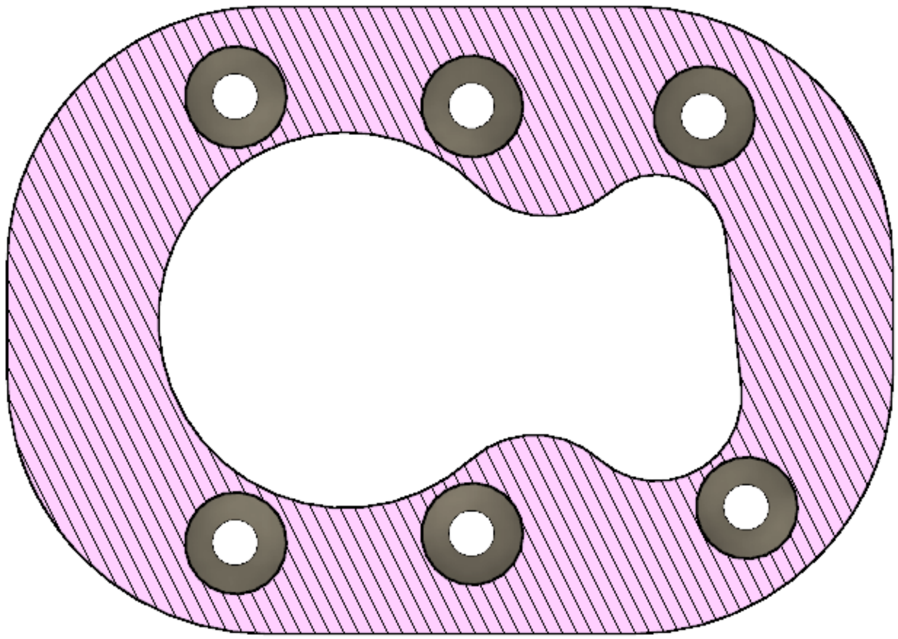

Figure 18: Section View of Housing

The housing features an asymmetrical goldfish-like slot that runs through the center of the housing; this is the main channel for the plunger to move through and space for the valves to open. The housing is cut into two halves which serve as methods to compress the seals in the plunger with a total of seven bolts. The seal compression will be discussed further in the plunger section. The main slot is machined while the halves are held together with bolts and pins to maximize machining accuracy. The housing includes a machined slot on the side which allows the dial to slide up and down. This allows the user to tell what the compression ratio is. There are two 1inch holes on the top of the housing, one is for mounting the Acme flange nut and the other is for allowing the spark plug cable to pass through the housing. Lastly, the outer profile is rounded to fit well on the engine without too many modifications. A detailed CAD design of the two halves of the housing is shown below in Figure 19.

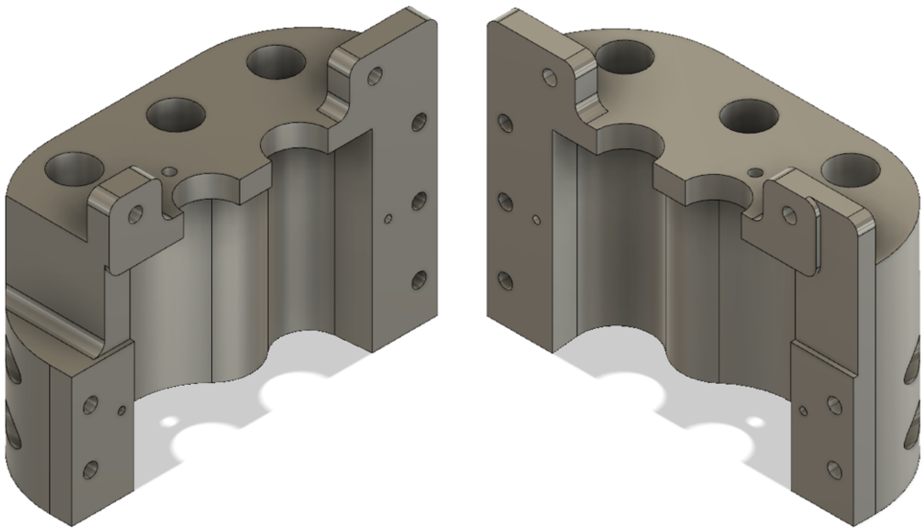

Figure 19: Housing Halves

Because of the complexity of the housing design, there were several design iterations, the major things that changed throughout the designs were the outer profile and the "goldfish" like slot. An example of one of the older design iterations is below in Figure 20. The main reason the team went with the design above is the simplicity of the outer face; it would be simpler to machine rather than the complex feature below.

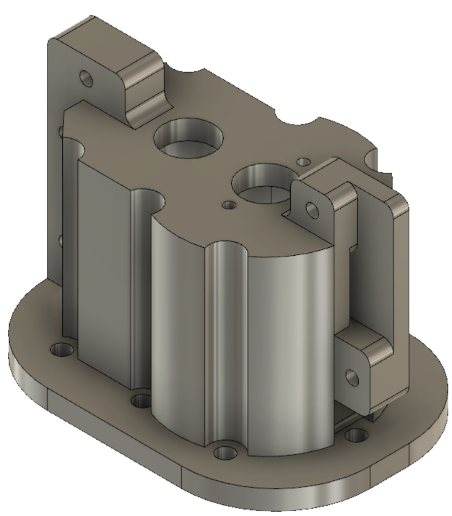

Figure 20: Older iteration of Housing Design

2.2.5 Plunger

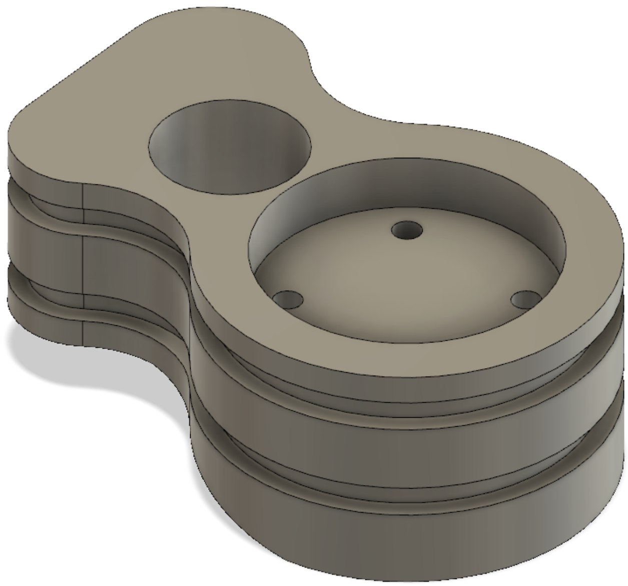

Figure 21: Plunger

The plunger was designed to fit within the slot that was made in the housing. It features a threaded bore in the center for the spark plug to be screwed into. There is also a large circle pocket on the top with four mounting holes for the Acme screw collet to be attached. Along the side profile, there are two channels that hold graphite packing material. These act as a seal between the plunger and the housing. As mentioned previously the seals are compressed so the depth of the channel was calculated to account for seal material squish. Lastly, the bottom face has an angled profile seen in Figure 22. This serves two purposes, one is to allow for the intake and exhaust valves to have enough space to open, and secondly, so we can create a smaller compression ratio than the engine's original compression ratio.

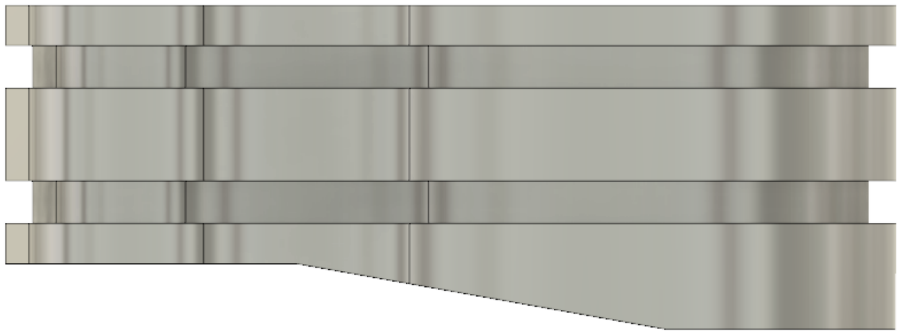

Figure 22: Plunger Side Profile

When designing the mechanism, the team completed some basic calculations to determine the range of motion required to achieve the desired range in compression ratio. As shown in Eq 1, below, the compression ratio of an engine is equal to the total volume of the engine over the head volume. Where the total volume is equal to the cylinder volume plus the head volume. The cylinder volume was calculated using Eq 2. To find the head volume the team split it up into two parts, the volume under the plunger and bore volume, shown below. The volume under the plunger was calculated using SolidWorks and the bore volume was found by multiplying the area of the bore times the height of the plunger.

Eq 1. $CR = \frac{Total\ Volume}{Head\ Volume} = \frac{Cylinder\ Volume + Head\ Volume}{Head\ Volume}$

Eq 2. $Cylinder\ Volume = \pi r^2 h;\ r = piston\ radius;\ h = piston\ stroke$

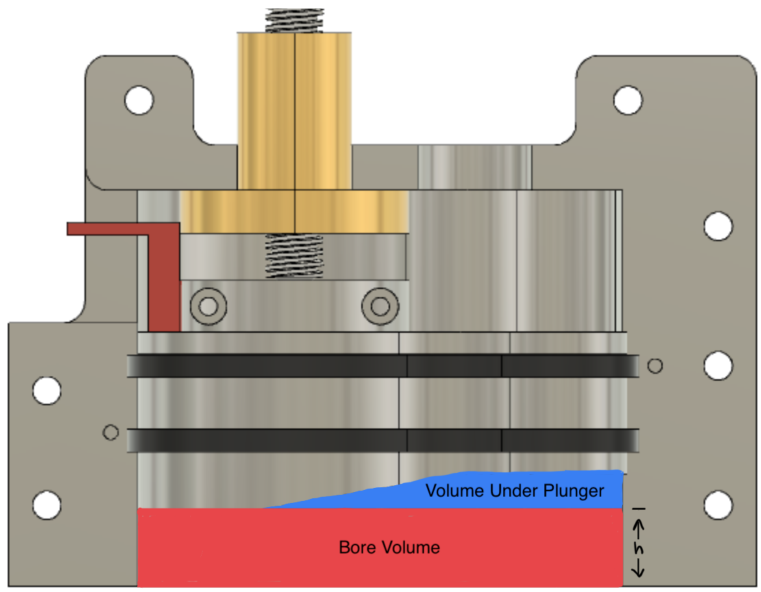

Figure 23: Volume Calculation of the Housing

Using these equations, the team was able to create an equation for the compression ratio as a function of the plunger height. Using this equation, we were able to determine the maximum plunger height, 2.7cm, needed to achieve a compression ratio range of 7:1 to 2:1.

2.2.6 Acme Screw and Plunger Collet

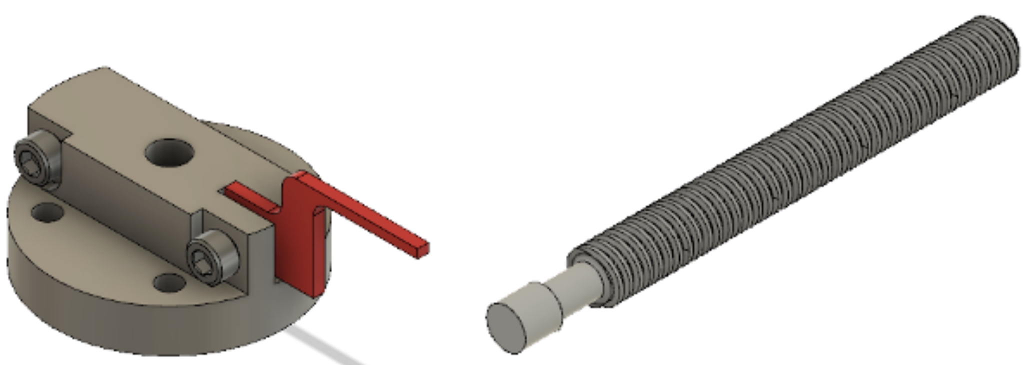

Figure 24: Acme Lead Screw and Plunger Collet

The last main components that needed to be designed and manufactured were the plunger collet and the profile of the steel precision Acme threaded rod. Both needed to fit together and act as a bearing. This is important because the Acme flange nut is attached to the housing, so the end of the Acme screw needs to be able to free spin. This was easier said than done and took the team some time and iterations to figure out. The final design features a 2-piece collet that has an inner channel profile allowing the Acme screw to free spin while still being captive as the screw moves up and down in the housing. The collet is attached to the plunger with four 10-32 bolts. There are also additional bolts that hold the two collet halves together. The Acme screw has a matching profile that fits into the collet. The section view is shown below in Figure 25. Lastly, a 3D printed nylon dial is attached to the collet.

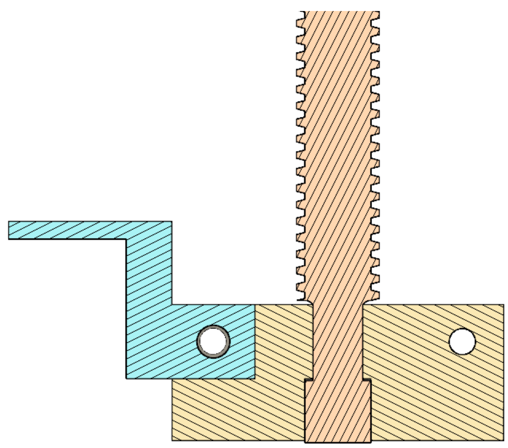

Figure 25: Acme Lead Screw and Collet Sub Assembly Cross Section

2.3 Manufacturing

2.3.1 Material Choice

The material used to machine the engine head was a primary design consideration. The head of the engine itself would need to withstand high levels of pressure and temperature; therefore, the material of choice would need to have the necessary mechanical and physical properties to be suitable for the application.

The material chosen was gray cast iron for its strength and thermal capabilities. It has an elastic modulus of 295 MPa, a Brinell Hardness number of 235 and a melting point of 1260 degrees Celsius; well above the maximum temperature that the temperature inside the housing of the custom engine head will reach [46]. Due to its high thermal conductivity, durability, wear resistance, cost, and ability to dampen vibrations, cast iron is a frequent choice in engine applications.

The original head for the lawnmower engine was manufactured out of aluminum. While aluminum is one of the easiest metals to machine, the team decided that is would not be suitable for our mechanism. Aluminum performs very poorly in sliding wear situations, such as our plunger. Aluminum also has a lower melting point than cast iron and can deform at high temperatures [34]. For an engine, which requires precise measurements of volume, any deformation would lead to failure. For these reasons, cast iron was chosen for the engine head mechanism; though it adds more weight, it is stronger and more stable.

2.3.2 CAM- Fusion 360

Computer Aided Design (CAD) focuses on the design of a product or part while Computer Aided Manufacturing (CAM) focuses on creating a profile to machine a product. CAM is the use of software and computer-controlled machinery to automate a manufacturing process [14]. There are three main components for a CAM system to function. The first is the software that tells a machine how to create a part by generating a toolpath. The second is the machinery that can turn raw material into a finished product. The third is the post processor which converts the toolpath into a language machine can understand.

The variable compression engine head was first designed in SolidWorks (CAD) where a 3D model was created. It was then loaded into the Fusion 360 CAM software which starts preparing the model for machining. Once all the tool paths required to shape the CAD part have been generated, which can be seen in Figure 26, they need to be converted to a language called G-code. This is a set of instructions that controls a machine's actions, including speed, feed rates, and coolant [14]. This program was then uploaded to the Haas CNC machines and run to cut each operation needed to produce the final parts. However, before running the CAM program on the Haas, the material for the parts needs to be selected along with the correct Speeds and Feeds for the necessary tools. The process of using the Haas CNC machines is detailed in Appendix B.

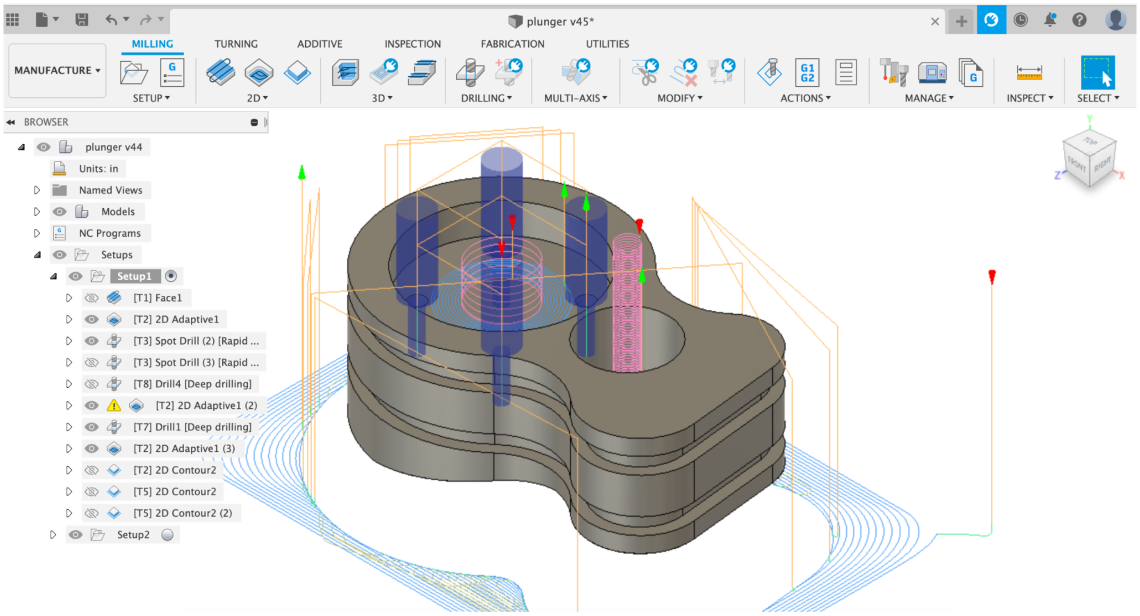

Figure 26: Generated Toolpath for Plunger from CAM

2.3.3 Feeds and Speeds

To machine the designed parts out of cast iron, custom tools were ordered, since Washburn shops did not have the necessary tools. The full list of ordered tools from McMaster Carr can be found in Appendix D. An end mill with a depth of cut of four inches was required for the deep pockets, plunger, and the outside contours of the housing of the engine head mechanism [12]. The endmill of choice was a ¾ inch high speed steel end mill, coated in Titanium Nitride (TiN) coating. High speed steel was chosen for its ability to cut through hard materials without chipping or receiving a large number of abrasions while maintaining a high hotness level – retains its durability at high temperatures [7]. Furthermore, the TiN coating on the tool itself has become quite popular in the machining industry as it keeps the tool in good condition for a longer time and provides other benefits such as thermal stability and a low coefficient of friction, making the cut smoother [41].

Before using one of the aforementioned cutting tools to create the designed parts from the cast iron stock, it was necessary to understand the tool's cutting speeds and feed rates. Speeds and feeds are the cutting variables used in every milling operation and vary based on tool type, cutting diameter, operation, material, etc. The wrong speeds and feeds can cause high thermal loads, decreased tool life, tool chipping and poor surface finish [20]. It is crucial to understand the right speeds and feeds for your tool and operation before starting machining.

The three main parameters which need to be monitored and changed in the CAM software – based on the selected tools and material – are cutting speed, spindle speed, and the chip load. Cutting speed, which is also referred to as surface speed, is the difference in speed between the tool and the workpiece. This is expressed in the units of distance over time or SFM (surface feet per minute). Next is the spindle speed, which is referred to as rotations per minute (RPM) and is based on the SFM and the cutting tool's diameter. Chip load per tooth is the amount of material that one cutting edge on a tool removes in a single revolution and is measured in inches per tooth (IPT) [10]. These values can be calculated with the equations seen in Figure 27.

SFM (Surface Feet per Minute)
$$\text{SFM} = \frac{\text{Cutter } \emptyset * \text{Speed (RPM)}}{3.82} \quad \text{Eq. 3}$$

RPM (Rotations per Minute)
$$\text{Speed (RPM)} = \frac{3.82 * \text{SFM}}{\text{Cutter } \emptyset} \quad \text{Eq. 4}$$

Chip Load Per Tool
$$\text{IPR} = \text{IPT} * \text{\# of Flutes} \quad \text{Eq. 5}$$

IPM (Inches Per Minute)
$$\text{Feed (IPM)} = \text{RPM} * \text{IPT} * \text{\# of Flutes} \quad \text{Eq. 6}$$

OR

$$\text{Feed (IPM)} = \text{RPM} * \text{IPR} \quad \text{Eq. 7}$$

Figure 27: Equation used to calculate Feeds and Speeds [37] [38]

Tool manufacturers also provide useful speeds and feed charts, based on tool material, cutting material and tool sizes, as seen in Figure 28. The feeds and speeds the team acquired from McMaster-Carr can be seen in Appendix E. These charts can be used to obtain the needed parameters. Once these values are determined, they are then input into the CAM software so that the data can be uploaded to the CNC machine.

MATERIAL	Hardness: 29-37 Rc (279-344 HBn)																
	SFM		Chip Load (IPT) by Dia			Depth of Cut		Chip Load (IPT) by Cutter Dia								Depth of Cut	
			0.015	0.031	0.047	Radial	Axial	0.062	0.078	0.093	0.125	0.187	0.250	0.375	0.500	Radial	Axial
CARBON STEELS		Slotting	.00006	.00012	.00018	1 x Dia	.20 x Dia	.00021	.00026	.00031	.00042	.00062	.00083	.00125	.00166	1 x Dia	.50 x Dia
Free-Machining/Low Carbon steels, 10xx - 1029 & all 10Lxx, 11xx - 1139 & all 11Lxx, 12xx - 1215 & all 12Lxx	600	Roughing	.00007	.00014	.00021	.30 x Dia	1 x Dia	.00024	.00031	.00036	.00049	.00073	.00098	.00147	.00196	.60 x Dia	1 x Dia
		Finishing	.00007	.00015	.00023	.13 x Dia	1 x Dia	.00027	.00034	.00040	.00054	.00081	.00109	.00163	.00217	.25 x Dia	1 x Dia
1030 - 1095, 1140 - 1151, 13xx, 15xx, 2xxx, 3xxx, 4xxx & 4xLxx, 5xxx & 5xLxx, 50xxx & 50Lxxx, 51xxx & 51Lxxx, 52xxx & 52Lxxx, 6xxx, 8xxx, 9xxx		Slotting	.00005	.00011	.00016	1 x Dia	.20 x Dia	.00019	.00024	.00028	.00038	.00057	.00076	.00114	.00152	1 x Dia	.50 x Dia
	200	Roughing	.00006	.00013	.00019	.30 x Dia	1 x Dia	.00022	.00028	.00033	.00045	.00067	.00089	.00134	.00179	.60 x Dia	1 x Dia
		Finishing	.00007	.00014	.00021	.13 x Dia	1 x Dia	.00025	.00031	.00037	.00050	.00074	.00099	.00149	.00199	.25 x Dia	1 x Dia
STAINLESS STEELS		Slotting	.00006	.00012	.00018	1 x Dia	.20 x Dia	.00021	.00026	.00031	.00042	.00062	.00083	.00125	.00166	1 x Dia	.50 x Dia
203 EZ, 303 (all types), 416, 416Se, 416 Plus X, 420F, 420FSe, 430F, 430FSe, 440F, 440FSe	450	Roughing	.00007	.00014	.00021	.30 x Dia	1 x Dia	.00024	.00031	.00036	.00049	.00073	.00098	.00147	.00196	.60 x Dia	1 x Dia
		Finishing	.00007	.00015	.00023	.13 x Dia	1 x Dia	.00027	.00034	.00040	.00054	.00081	.00109	.00163	.00217	.25 x Dia	1 x Dia
201, 202, 203, 205, 301, 302, 304, 304L, 308, 309, 310, 314, 316, 316L, 317, 321, 329, 330, 347, 348, 385, 403, 405, 409, 410, 413, 420, 429, 430, 434, 436, 442, 446, 501, 502		Slotting	.00005	.00011	.00016	1 x Dia	.20 x Dia	.00019	.00024	.00028	.00038	.00057	.00076	.00114	.00152	1 x Dia	.50 x Dia
	200	Roughing	.00006	.00013	.00019	.30 x Dia	1 x Dia	.00022	.00028	.00033	.00045	.00067	.00089	.00134	.00179	.60 x Dia	1 x Dia
		Finishing	.00007	.00014	.00021	.13 x Dia	1 x Dia	.00025	.00031	.00037	.00050	.00074	.00099	.00149	.00199	.25 x Dia	1 x Dia

Figure 28: Feeds and Speeds Chart [39]

2.3.4 Manual Mill/ lathe Machine

For some operations such as tapping holes and facing bar stock, the team made use of both a manual mill and manual lathe. The manual mill is like the Haas mills that were used however they lack the computer-controlled aspect. Instead, the machine makes use of a human operator to control the motion of the table. Dimensions are read from the design drawings and transposed to the manual machine; a CAM program is not required. The operator spins a series of handles which each control either the X, Y or Z axis of the machine. The desired tool was placed into a collet and ultimately into the spindle where the proper RPM was selected. The stock is placed into the vice of the mill and the tool is then pushed through the stock to form the shape of the desired parts [4]. A picture of a manual mill can be seen in Figure 29. The team mainly used the manual mill to tap our drilled holes. This was done because taps are extremely fragile and tend to break inside the parts and are hard to remove broken bits. By making use of the manual machine, we had a better feel for how the operations were going and prevented any taps from breaking.

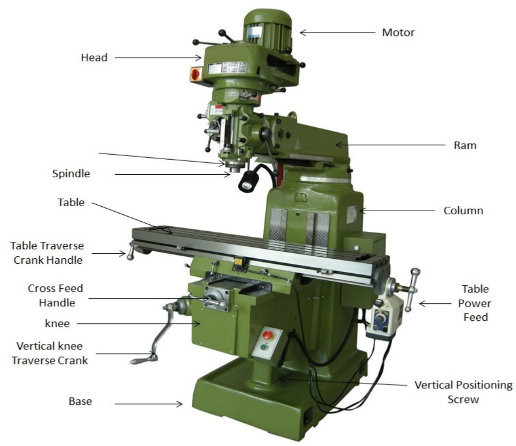

Figure 29: Manual Milling Machine [32]

A manual lathe was also used to turn the ends of the steel Acme threaded rod as well as the threaded rod collet. A manual lathe is very similar to a manual mill however the lathe spins the stock instead of the tool. The manual lathe still makes use of an operator spinning handles to adjust different parameters of the machine. The team loaded different bar stock into the lathe and used different inert tips to form shapes in the stock to create our parts [45]. An image of a manual lathe can be found in Figure 30.

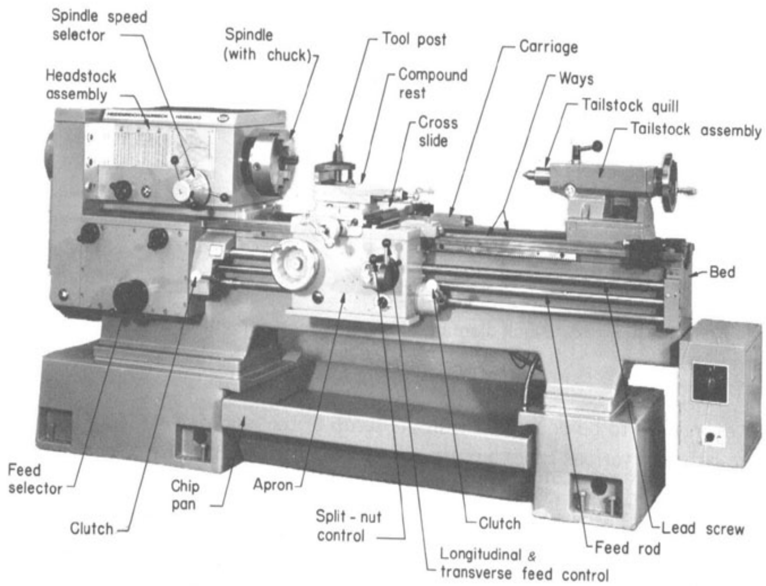

Figure 30: Manual Lathe Machine [16]

2.3.5 Plunger Fixture

To complete the machining process of the plunger, a custom fixture would have to be crafted to machine the profile along the bottom side of the plunger. Since the top machined half would already have the goldfish shaped contour, the square vice would not be effective in securing the part for the bottom to be machined. Figure 31 shows the 3D model of the fixture that would fit around the plungers outside contour.

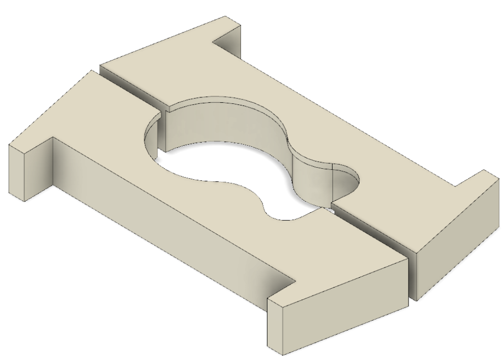

Figure 31: 3D Model of Plunger Fixture

This custom fixture was 3-D printed due to the ease of design and manufacturing through CAD and 3D printers. In addition, there would be a large amount of force applied to the fixture when tightening the vice to secure the plunger. Therefore, nylon was the chosen filament material due to its high strength and durability [8]. It was critical that the fixture would not crack before or during the operation. Due to nylon already having a high elastic modulus and the size of the fixtures being relatively large, the parts were printed at 40% infill to be time efficient.

3. Results

The team successfully manufactured the housing and partly completed the plunger. Some unexpected issues were encountered that hindered progress and prevented the team from completing everything we had hoped to.

The first issue encountered was the slow machining time of cast iron. Before starting the manufacturing process, the team was unaware of how long it actually took to cut cast iron. The cast iron stock had to first be cut into two separate halves as seen in figure 32, one for each side of the housing. Due to the hardness of the material, this was a very slow and tedious process taking the team a total of 3 hours to cut through the iron. Most of the other operations on the CNC machine took anywhere from 1-3 hours to run. For example, the facing operations on the stock each took 40 minutes and had to be run 4 times.

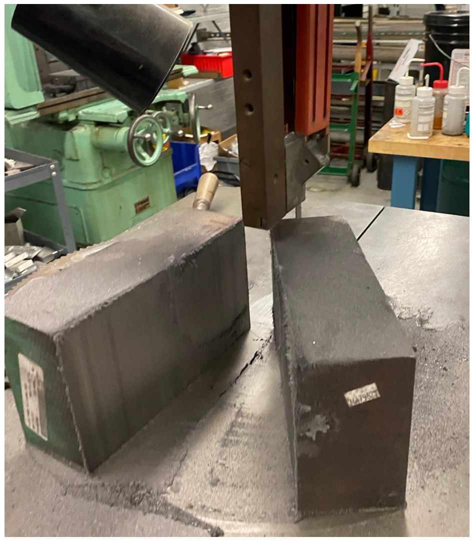

Figure 32: Bandsaw Cutting Block of Cast Iron

The next issue the team ran into was first encountered while completing the facing operations. Since this was our first operation run on the Haas CNC machines, we had some difficulties finding the proper feeds and speeds as well as step down/over for the face mill. Cast iron isn't a very common material to be cut in Washburn Shops so most of the lab assistants were unable to assist us in running our operations. The feeds and speeds provided to us for cutting cast iron were not accurate and led to the team stalling the machine. During the first pass, the CNC machine was set to remove too much material, seen in Figure 33, resulting in the machine shutting off due to a spindle stall.

Figure 33: Facing Pass Where Machine Crashed

While running the drilling operation to create bolt holes, the team broke a drill bit and got it stuck in one of the holes. This was also the result of running the tool with incorrect feeds and speeds. The drill was spinning at too high of an RPM causing the bit to micro-weld to the cast iron and ultimately break. The broken drill bit was extremely difficult to get out of the hole because it was made from hardened steel. The team proceeded to use a combination of methods to try to clear the hole. A Dremel with a grinding bit was used along with the manual mill to chip away at the broken bit. The manual mill allowed for more control and allowed us to feel before another drill bit broke. The team also drilled a hole on the opposite side to try and punch out the broken bit, as depicted in figure 34. The combination of techniques ended up being successful and allowed the team to remove the drill bit and salvage the piece of cast iron. After this, the team started to calculate our own feeds and speeds instead of trusting the incorrect information given to us. Conducting our own calculations worked very well and the team did not run into anymore problems due to incorrect feeds and speeds.

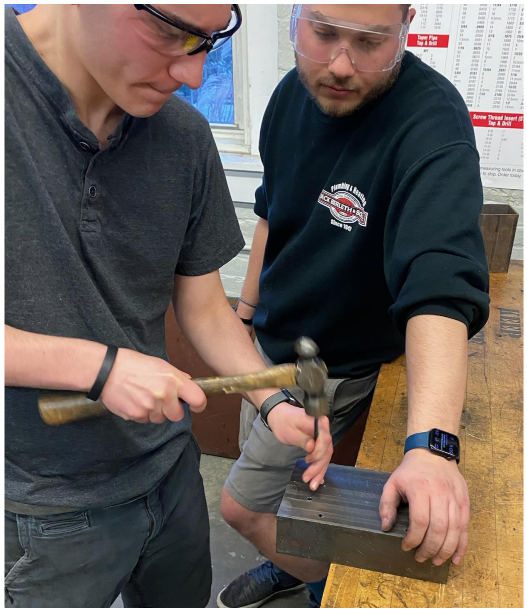

Figure 34: Hammering Out Broken Drill Bit

The largest issue the team ran into came after cutting out the goldfish shaped bore in the housing. When we measured the completed bore, we noticed that the bottom of the hole was significantly smaller than the top. The team determined that this was due to the endmill deflecting during the operation. This was an issue that would have caused the plunger to bind and have sealing problems resulting in the engine head not functioning. To fix this issue the team coated the inside plunger pocket with paint and proceeded to remove extremely small amounts of material at a time with spring passes. The painted pocket can be seen in figure 35. The paint helped to show where the material was being removed from while straightening out the pocket. This helped to prevent the team from removing too much material and making the pocket bigger than it already was.

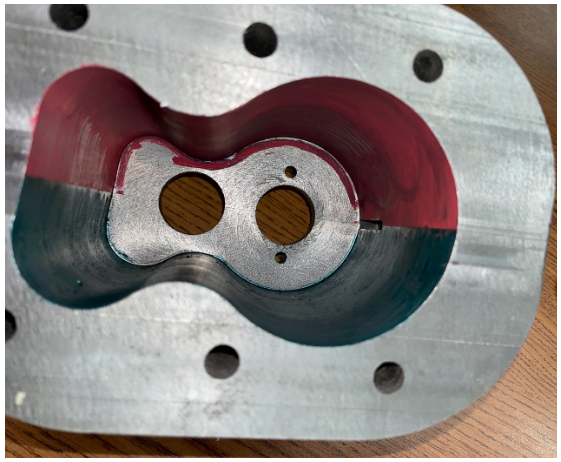

Figure 35: Painted Plunger Pocket

While working to machine the plunger, the team ran into another issue which resulted in the plunger being only partly completed. While the tool defection was still present during machining, the plunger was thinner and had dedicated seals, so it was less of an issue. However, the tolerances required for the snug fit of the plunger inside the housing proved to be very difficult. After cutting the slots to the anticipated depth for the seals, the team attempted to assemble the housing around the plunger and found it almost impossible to move the plunger. This meant that more alterations and adjustments are necessary to find the optimal depth of the seal slots. It was determined that the best course of action was to not cut the plunger from the base stock since there would not be any way of adjusting the depth of the seals. Since the project was going to need more work done and possibly another group to complete it, the plugger block will be passed on to another team to adjust the seals. There are some suggestions and recommendations which can be found in the future work section highlighting how the plunger can be redesigned as well as how to proceed with the current part.

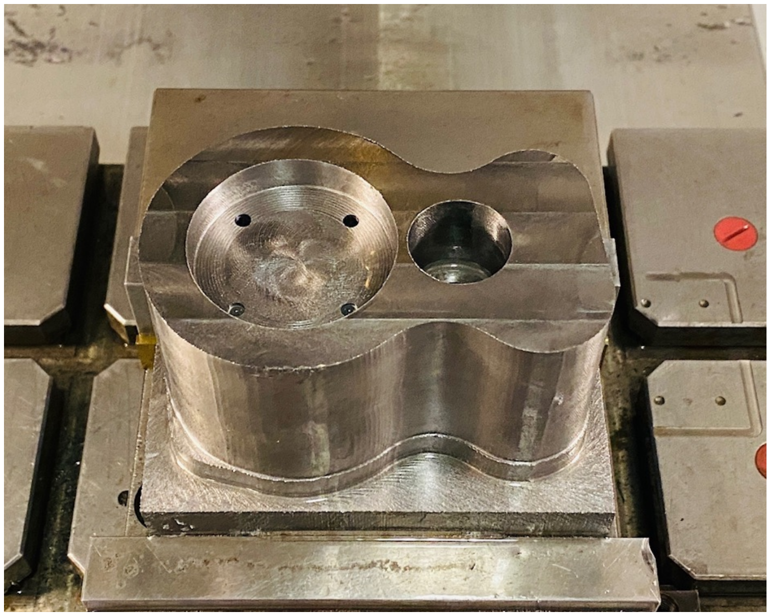

Figure 36: Plunder Attached to Stock Block

The final issue the team ran into was when the Plunger collet and steel Acme screw were being machined. The Plunger collet was successfully assembled to the point where the steel profile was ready to be created. The team started creating the flange, seen in figure 37, on the steel Acme screw first. Quickly the team realized the wedge shape didn't have a sharp enough angle and would be pulled right through the plunger collet. This led to design changes in the steel Acme shape which can be seen in the design section. This new shape was produced on the manual lathe and repeated in the plunger collet shown in figure 38. While the theory worked, the contact points for the steel Acme rod to the plunger collet are very small and could fail in future use. This led the team to design a more versatile and stronger mechanism to move the plunger in the housing.

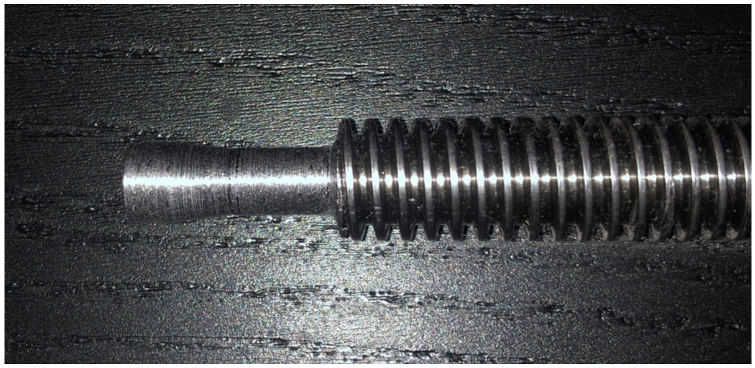

Figure 37: Wedge Profile Cut into Steel Acme Screw

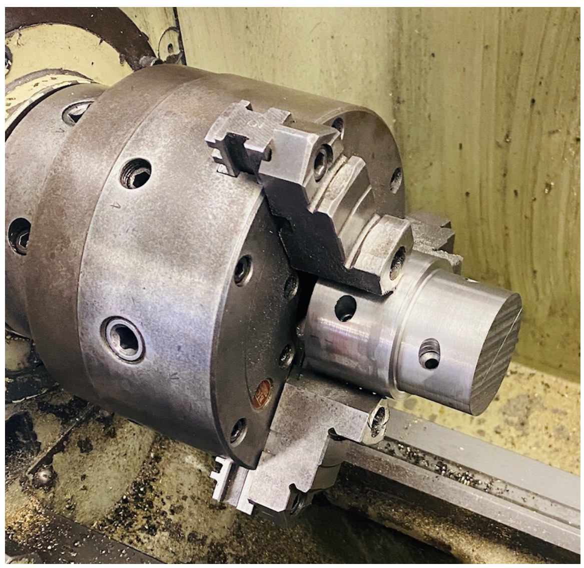

Figure 38: Plunger Collet in Manual lathe

To solve this issue, the team re-designed the plunger collet. The team changed the profile on the end of the Acme screw from the conical one shown above to the cylindrical one shown below, figure 39. The collet was also redesigned to accommodate the change in the screw and to fit two additional bolts to increase the strength of the assembly. The completed plunger and collet assembly is shown below in figure 40.

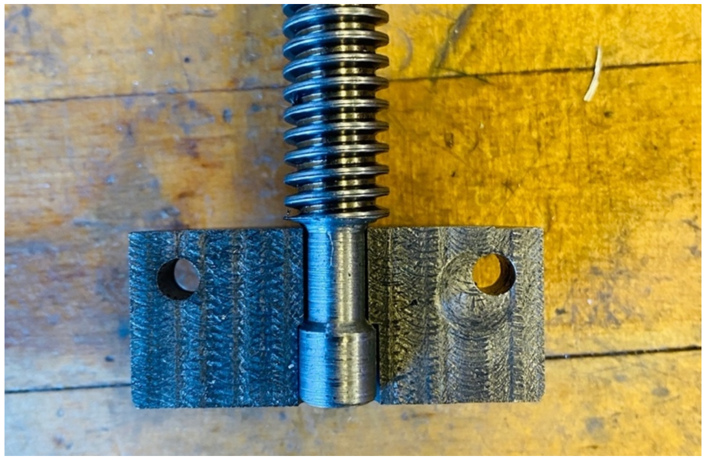

Figure 39: Final Acme Screw Profile

Figure 40: Final Plunger Collet

4.0 Conclusion

The production of the engine head mechanism has made significant progress towards being ready for testing on the lawnmower engine mechanism the team was able successfully prototype the mechanism to achieve a 2:1 to a 7:1 compression ratio using CAD software. Based on the design, the team was able to complete the toolpaths for each part of the mechanism machined using the Fusion 360 CAM software. Furthermore, all the necessary tools for each operation for cast iron blocks have been obtained.

The mechanism consists of 3 major pieces referred to as the housing, the plunger and the Acme rod attached to the plunger collet. The majority of the housing was completed using the ¾ inch HSS end mill, aside from several drilling operations on the top face and the facing operations. The tolerances for the Acme nut, screws, and pins were met and the two halves fit together adequately. However, due to the larger cutting depth, the tool deflected as the bottom of the tool would tend to bend away from the part. This issue had the largest impact on the width of the pocket for the plunger. Since the dimension of the pocket is critical for the seals, the team decided to make a few more finishing passes with a very small step over length in order to diminish as much of the deflection as possible.

This directly affected the machining process of the plunger. The top profile of the plunger has been machined and the groves have been cut into the side of the plunger. However, the team was not satisfied with how the plunger fit in the housing; therefore, the plunger was left on the stock for future teams to continue the work, focusing on the depth of the groves. The correct protrusion length of the seal will allow the plunger to be easily manipulated via manual power, using the handwheel. The toolpaths for the bottom side of the plunger are finalized and are ready to be machined once the necessary depth of the groves is determined. The plunger fixture that was 3-D printed out of nylon will be used to mount the plunger in the machine vice.

Lastly, the Acme screw, Acme nut, and plunger collet were successfully machined using the manual mill and the manual lathe. Two holes were drilled into the Acme nut to be mounted on the housing. The tolerance and dimensions for those holes were accurate, allowing a secured fit.

The Acme screw was cut down to the length of about 5 inches and was machined to have a profile at the bottom to allow it to be secure in the plunger collet while being able to free spin. The tolerances for that process were met, allowing the Acme rod, Acme nut, and the plunger collet to work in sync in order to raise and lower the plunger through the use of the handwheel.

5.0 Future Work

Over the course of this MQP, it was determined that several areas of work could have been done differently or require additional work and will need to be addressed by a future team.

The biggest challenge during the current MQP period was the tool deflection that was seen while using the CNC machines. It was determined that the best method to eliminate this issue would be to use a machine called the Wire Electrical Discharge Machine (EDM). This machine works by using a wire to release an electrical discharge between itself and the workpiece. Through heat and electrical discharge, the wire can be used to cut the pocket out without causing deflection [27]. Other methods to minimize the deflection, in the case where a Wire EDM is not accessible, would be to use a reduced shank carbide end mill as opposed to the high-speed steel end mill. The carbide end mills allow RPM up to 4 times as high as high-speed steel, allowing for better surface finish and less tool deflection. The deflection is a function of tool length, using a reduced shank end mill will eliminate excessive force caused by the endmill coming in contact with a larger area. This is because the diameter of the cutting edge is larger than the shank so that only a certain portion of the endmill will be in contact with the workpiece at all times. The operation with the reduced shank endmill will need to be run with a small step down and step over length. This method will greatly increase the manufacturing time of the part but will work towards minimizing the deflection in the pocket.

The elimination of deflection will lead to fitting the plunger inside the housing. The future team or someone else will need to determine the necessary slot depth for the seals so that the plunger can move up and down with the use of the handwheel, while also ensuring it does not leak. After finalizing the slots and seals, the group will need to cut off the plunger from the stock and machine the contour on the bottom of the plunger. The team will need to make use of the plunger fixture, to securely mount the plunger on the vice, since the top half will have the curved contour and will not be secured by the square vice.

Once the two items mentioned above are made the team can begin to attach the head mechanism to the lawnmower engine. To do this the team will need to modify the lawnmower engine to allow the head to fit. This includes the spark plug wire, the pull start covers, and the gas tank.

After mounting the head on the engine, the team can test if the engine runs while moving the plunger up and down. After ensuring the engine runs as intended the team can conduct several tests to evaluate the engine performance at different compression ratios.

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Appendix A: Engine Terminology

Piston: A mechanism that slides up and down a cylinder, transferring energy from the combustion process to a crankshaft that it is connected to.

Bore: The diameter of the cylinder

Crank Shaft: The mechanism that controls the pistons movements.

Piston Rings/Seals: Used to seal the combustion chamber and prevent excessive oil from leaking into the chamber.

Top Dead Center: Term for the position of the piston at the very top of its stroke.

Bottom Dead Center: Term for the position of the piston at the very bottom of its stroke.

Combustion Chamber: The volume above the piston when at bottom-dead center, including the cylinder head.

Cylinder Head (engine head): A part that is bolted to the top of the engine, covering the combustion chamber and the piston. Houses the spark plug and provides a path for air to flow into the cylinder during the intake stroke and the exhaust gasses to be expelled during the exhaust stroke.

Head gasket: Contains the pressure created in the combustion chamber when the spark plug ignites the fuel and air mixture to achieve the desired compression ratio.

Intake valve: Regulates the flow of air/fuel mixture into the combustion chamber.

Exhaust valve: Regulates the flow of exhaust gasses out of the combustion chamber.

Spark plug: Ignites the air/fuel mixture during the combustion process creating a force that pushes the piston down, generating power.

Carburetor: A device that blends the correct ratio of air and fuel for an internal combustion engine [6].

Appendix B: CNC Machining Process

The machine set up is a systematic process that is essential to manufacturing a part with precision and accuracy. The following step describes the process the team took to machine the necessary parts:

1. The machine was turned on and the emergency stop was released. The power up cycle was then run to get the machine fully functional.
2. If not already loaded, the machine vice was fastened into the CNC machine. The team would also use an edge finder to square off the vice.
3. The tool that was needed for the operation was loaded into the appropriate collet and chucked up into a tool holder. The tool was tightened using a torque wrench.
4. The team then loads the tool into the machine, making sure that the groves on the side of the tool holder were lined up with the divots on the machine. This allowed the tool to lock into the machine when the suction is activated.
5. The tool offsets were then completed, measurements such as tool length, diameter, and tool number were pieces of data necessary to accurately send tool data to the machine (g-code). The tool would then be automatically probed to determine the center point of the tool.

6. Once the tool offsets were completed, the part was then placed in the machine vice. To avoid a vice crash – in the case where the cut is deeper than the exposed depth of the part – the team would need to make use of parallels, to raise the height of the part.
7. The part is then tightened onto the vice using the correct technique.
8. The machine is then cycled to the machine probe tool and the probing program is run. It was important to set acceptable length measurements for width, length, and depth to prevent the probe from crashing, while being able to tap off to the appropriate faces of the part.
9. The tool path would then be loaded onto the CNC machine and simulated using the machine commands. The team could check if the appropriate program was loaded on the machine and if any tool crash into the part were to occur.
10. Once the simulation was completed and looked adequate, the operation would begin. The team would monitor the distance to go tab to make sure the tool would begin the cut at the appropriate height and avoid any mishaps.

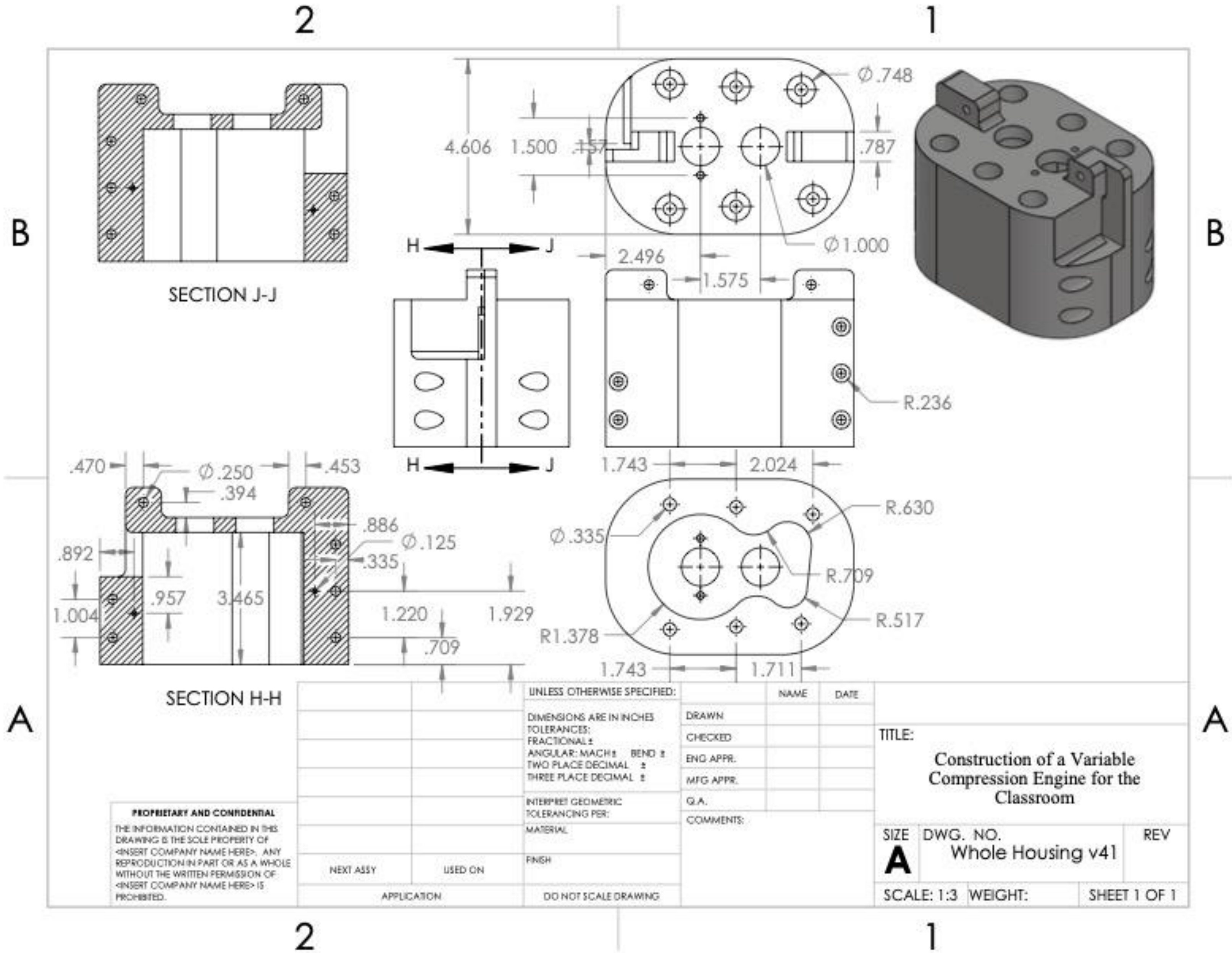
Appendix C: Bill of Materials

Material	Dimension	Part number	Quantity	Price	
O-ring stock-sqr	3/16"	1177N14	10ft	$17.20	https://www.mcmaster.com/1177N14/
Low-Friction Oil- and Water-Resistant Packing Seals	3/16"	9518K82	10 ft	$27.45	https://www.mcmaster.com/9518K82/
O-ring stock-round	3/16"	96505K24	10ft	$9.00	https://www.mcmaster.com/96505K24/
Cast Iron housing billet	71/4"x61/4"x12"	N/A	1	Peterson steel	https://www.mcmaster.com/cast-iron/
Cast Iron plunger billet	2 1/4"x41/4"x12"	N/A	1	Peterson steel	https://www.mcmaster.com/cast-iron/
Cast Iron bar stock for nut	21/4"x12"	8909K51	1ft	$35.10	https://www.mcmaster.com/8909K51/
Acme screw	1/2"-10--2 ft	98935A911	1	$6.52	https://www.mcmaster.com/98935A911/
Acme nut	1/2"-10 Bronze	97790A110	1	$104.48	https://www.mcmaster.com/97790A110/
Head pins	1/8" dia x 5/8"	98381A306	1-Pack of 25	$8.28	https://www.mcmaster.com/catalog/98381a306
Bolts for plunger and nut	10-32 x 7/8"	91251A346	1-Pack of 50	$8.00	https://www.mcmaster.com/catalog/91251a346
Bolts for housing	1/4"-20 x 1 1/4"	96006A718	1-Pack of 10	$4.77	https://www.mcmaster.com/96006A718/
Nuts for housing	1/4"-20 nylon nut	90630A110	1-Pack of 25	$4.49	https://www.mcmaster.com/catalog/90630a110
Aluminum Hand Wheel	6” Diameter	3724T59	1	$79.09	https://www.mcmaster.com/3724T59/
Total				$304.38	

Appendix D: McMaster-Carr Tool list

	Tool	SFM Ft/Min	RPM Rotation/Min	FPT
1	3/8” chamfer mill	250	2546	0.0022
2	¾” x 4” Sq Endmill HSS	100	509	0.0026
3	3” face mill	4252	5414	0.003
4	¼” Sq Endmill HSS	100	1000	0.0003
5	¼” Ball Endmill HSS	100	1000	0.0003
6	½” Sq Endmill HSS	100	600	0.003
7	3/16” Key slot cutter HSS	300	764	0.0002
8	1/8” Drill	115	3514	0.005
9	¼” Drill	115	1757	0.008
10	0.472” Drill	617.8	5000	0.008
11	½” Drill	90	688	0.01
12	0.159” Drill	80	1922	0.003
13	5/8” Drill	90	550	0.009
14	0.2” Drill	90	1719	0.005
15	11/32” Drill	100	1111	0.006
16	0.124” Reamer	162.3	5000	0.008
17	0.126” Reamer	164.9	5000	0.008

Appendix E: Drawings


SECTION J-J
SECTION H-H
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1.500
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.787
Ø.748
Ø1.000
2.496
1.575
R.236
1.743
2.024
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Ø.250
.394
.453
.886
Ø.125
.335
.892
.957
3.465
1.004
1.220
1.929
.709
Ø.335
R.630
R.709
R.517
R1.378
1.711
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
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CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
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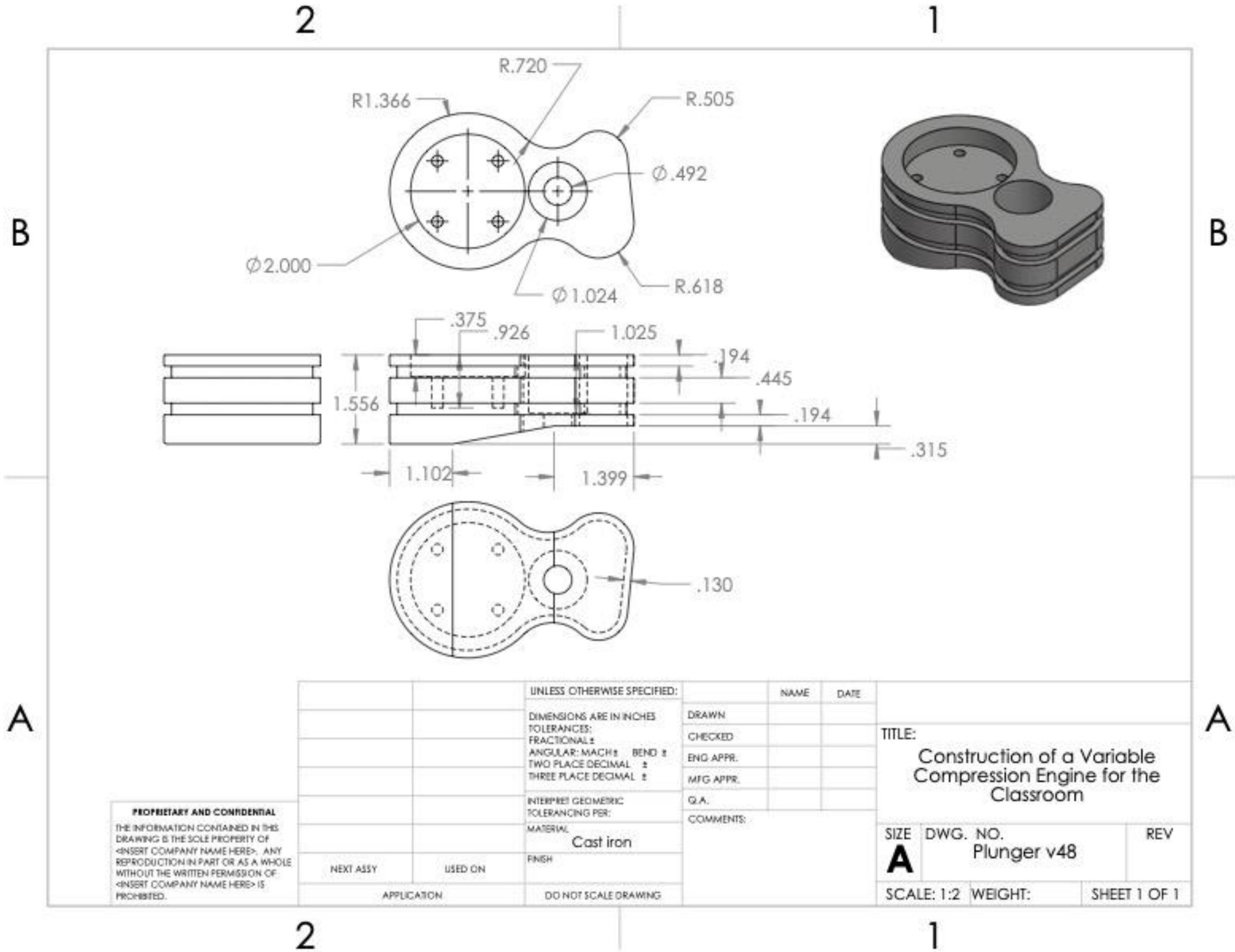
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
TITLE:
Construction of a Variable Compression Engine for the Classroom
SIZE
A
DWG. NO.
Whole Housing v41
REV
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1


R.720
R1.366
R.505
Ø.492
Ø2.000
Ø1.024
R.618
.375
.926
1.025
.194
.445
1.556
.194
.315
1.102
1.399
.130
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Cast iron
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ENG APPR.
MFG APPR.
Q.A.
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Construction of a Variable Compression Engine for the Classroom
SIZE
A
DWG. NO.
Plunger v48
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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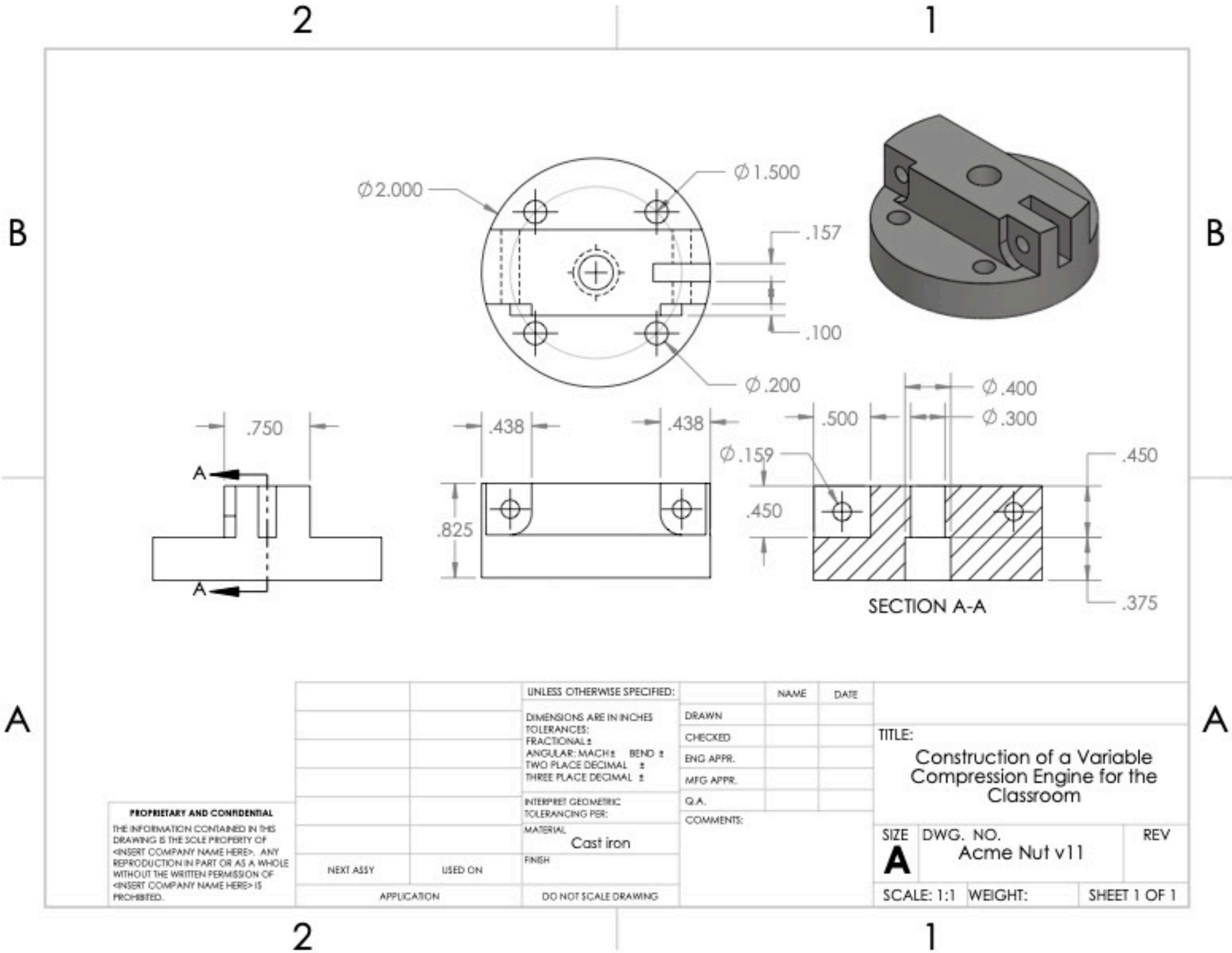
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SECTION A-A
PROPRIETARY AND CONFIDENTIAL
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MATERIAL
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FINISH
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Construction of a Variable Compression Engine for the Classroom
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Acme Nut v11
REV
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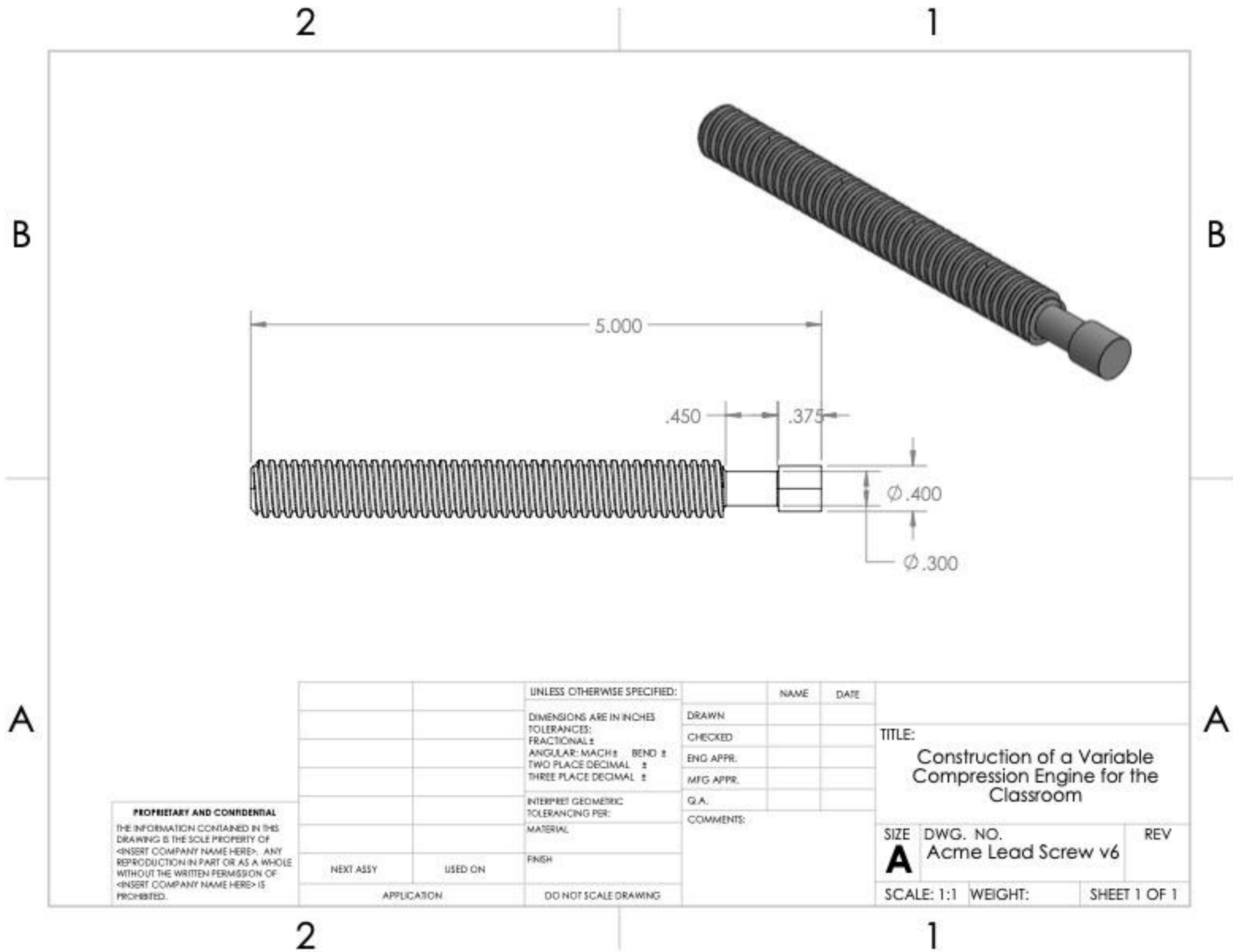
SHEET 1 OF 1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PROPRIETARY AND CONFIDENTIAL
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USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Construction of a Variable Compression Engine for the Classroom
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REV
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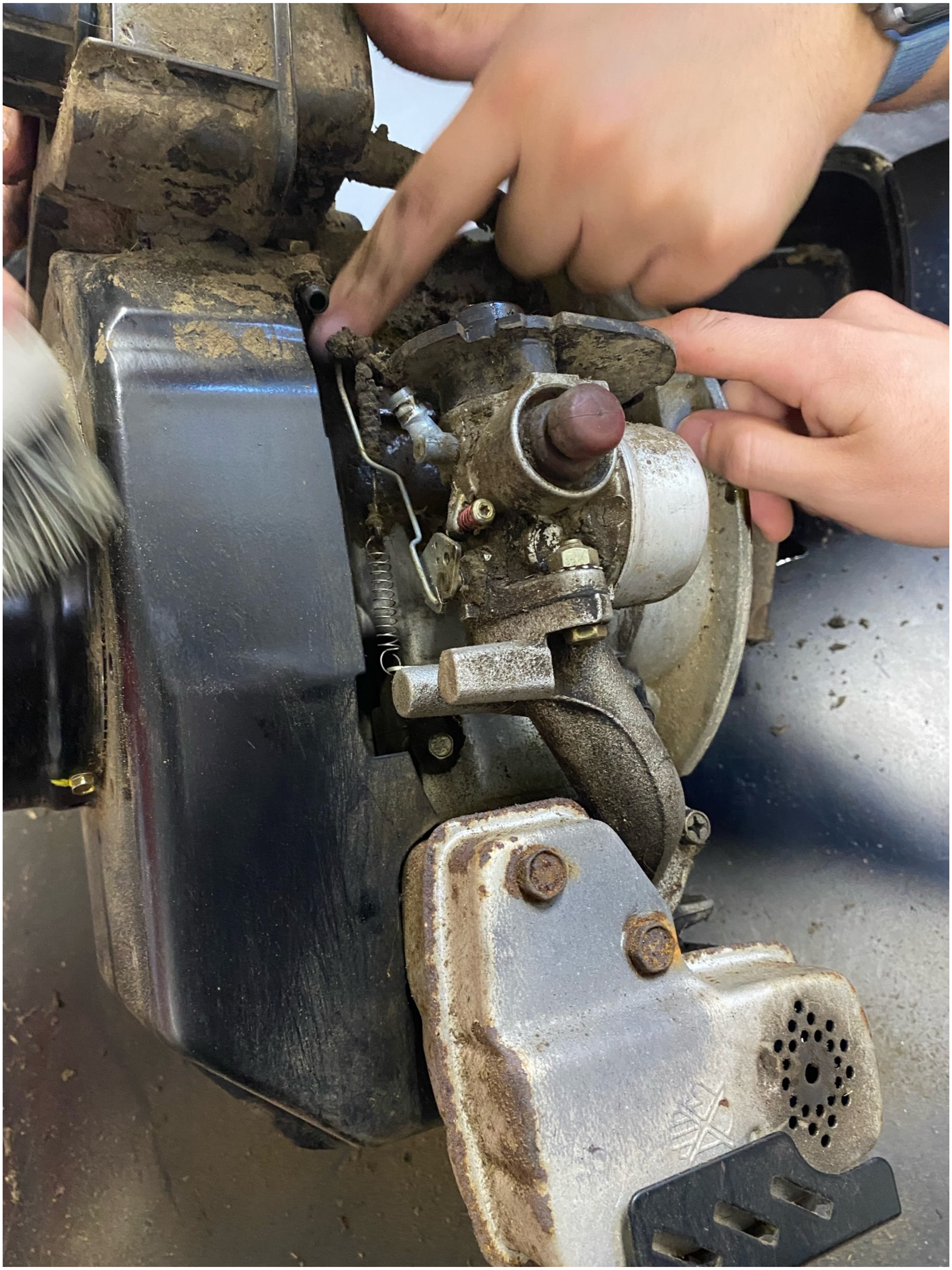
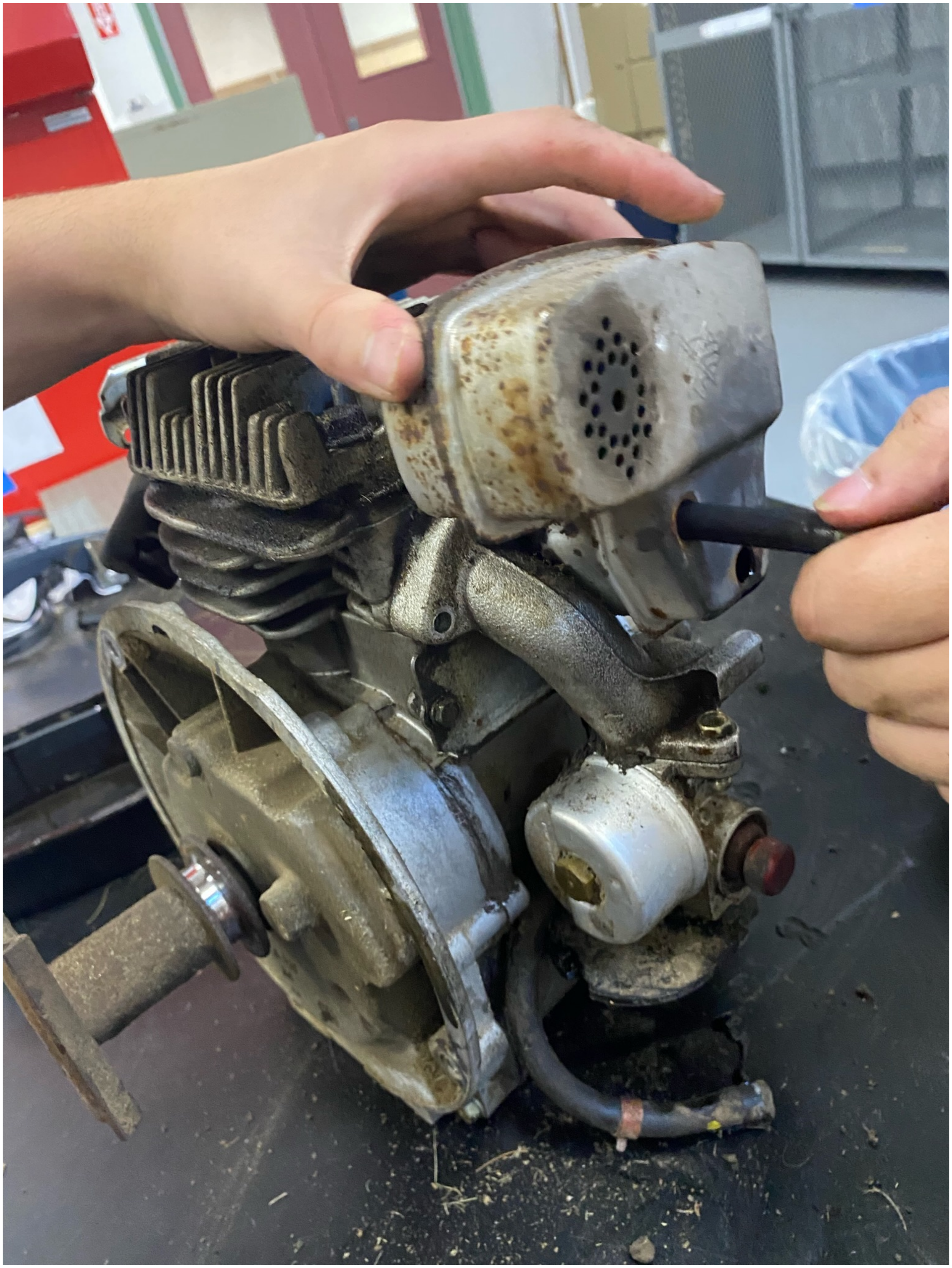
SHEET 1 OF 1

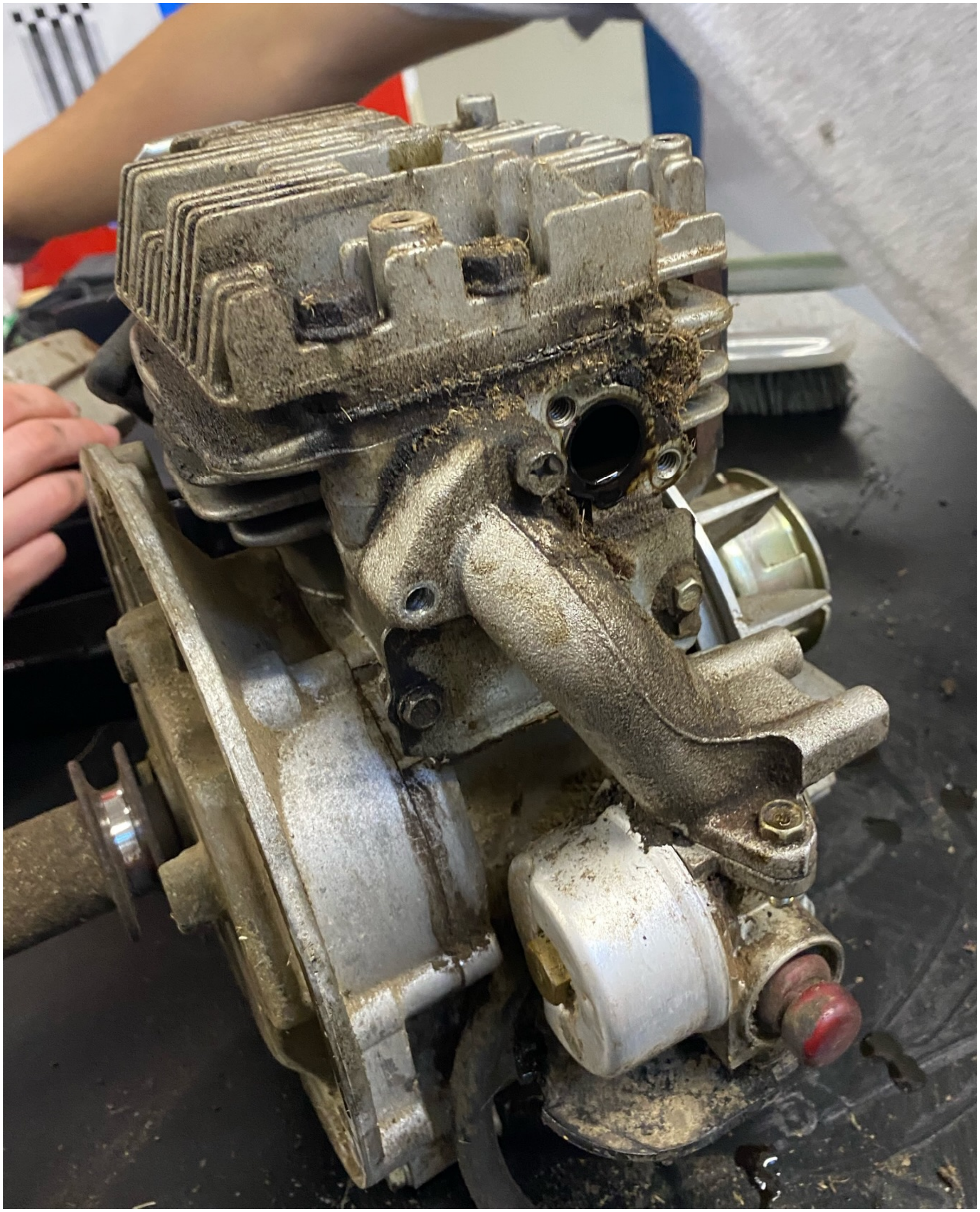
Appendix F: Additional Pictures

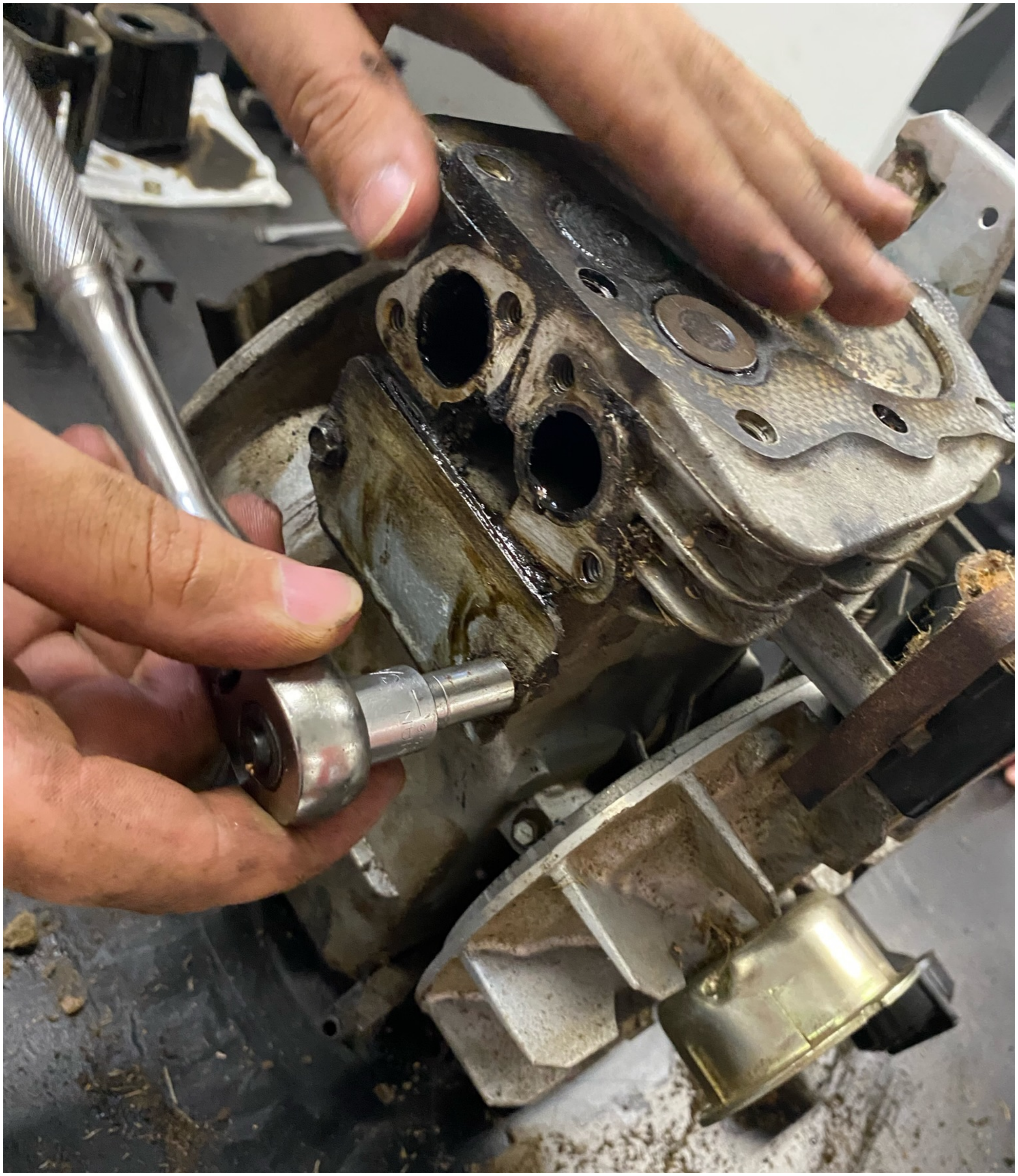


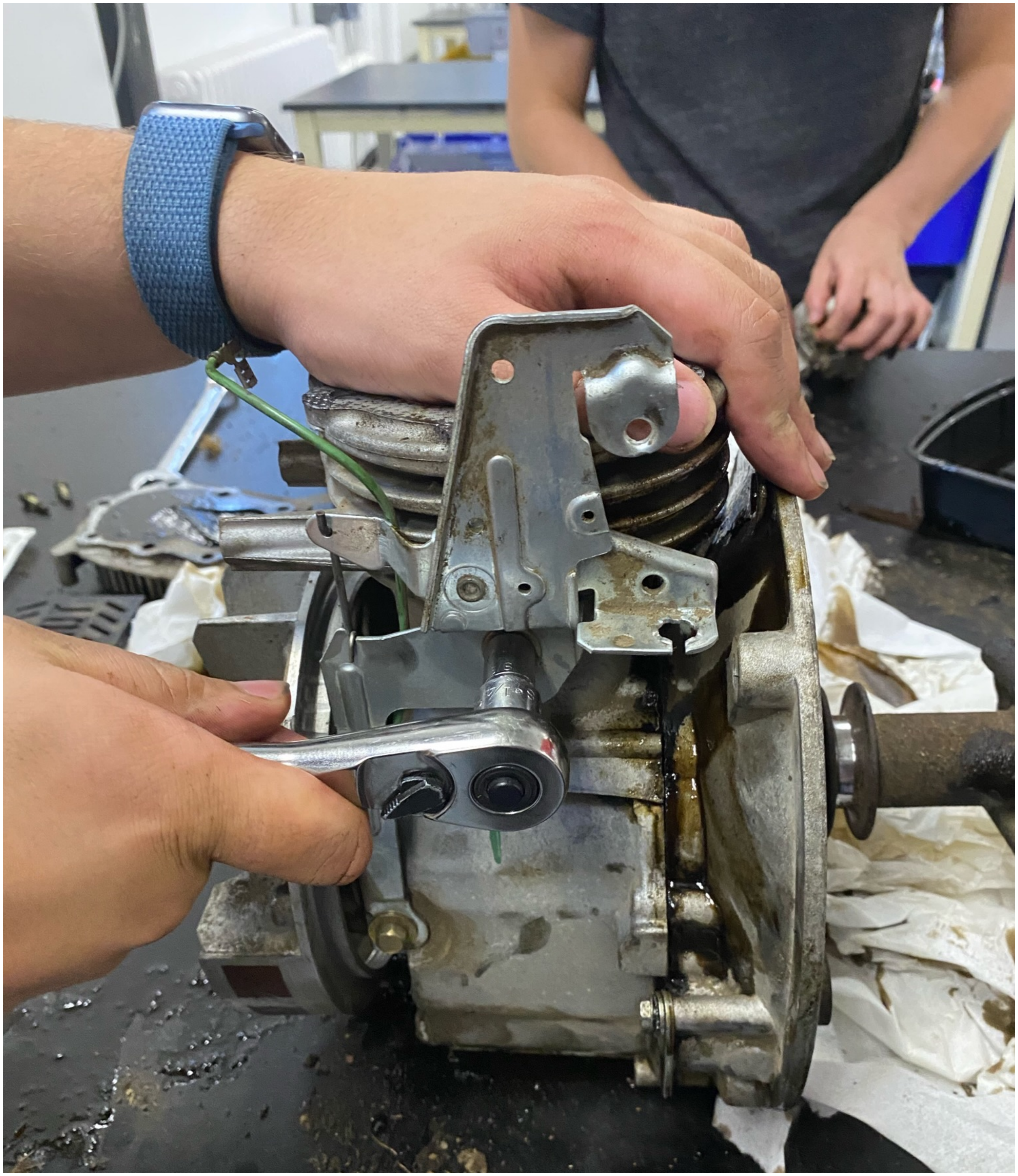

ENGINE
OIL


HOT







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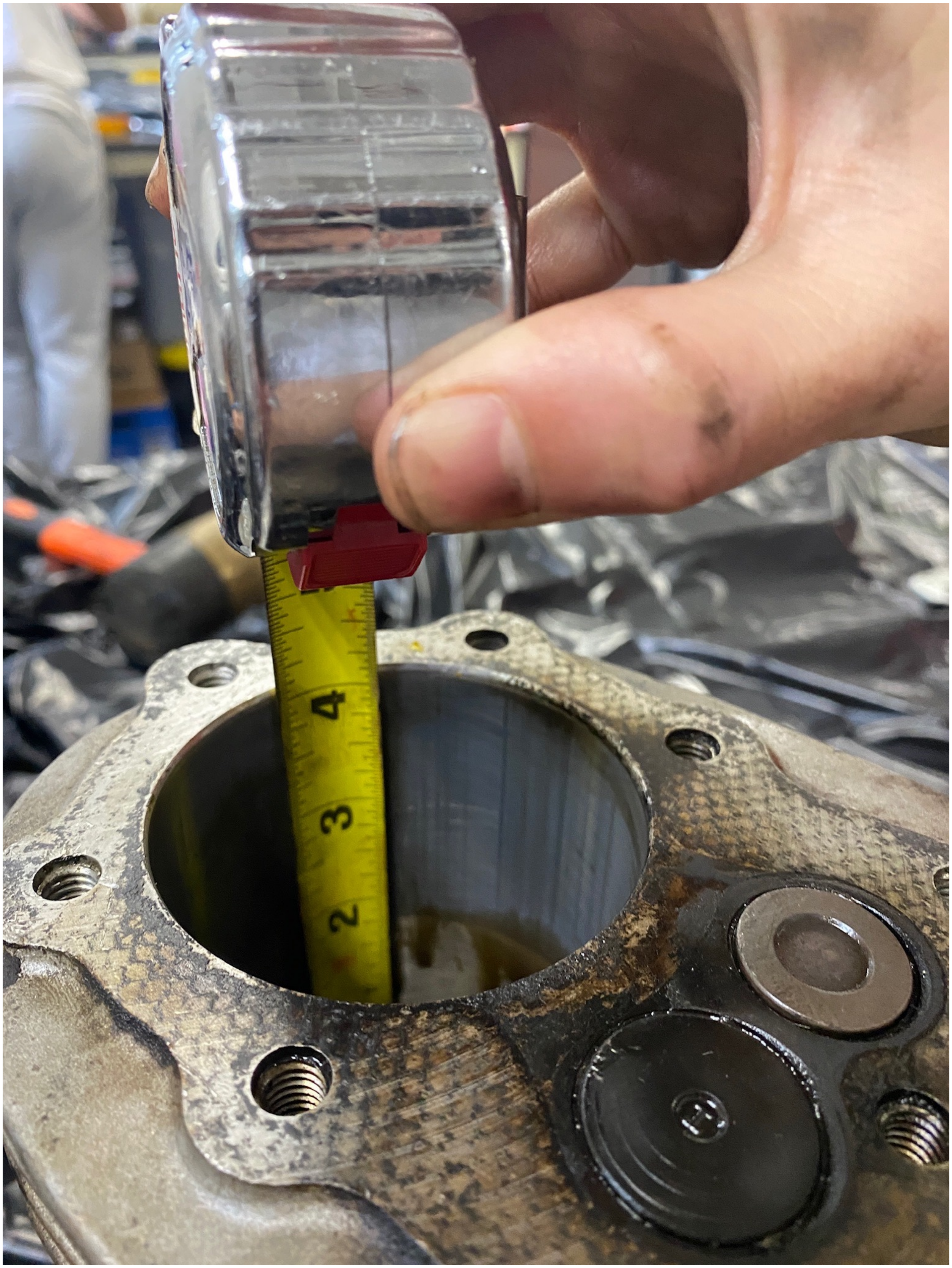
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12 ft
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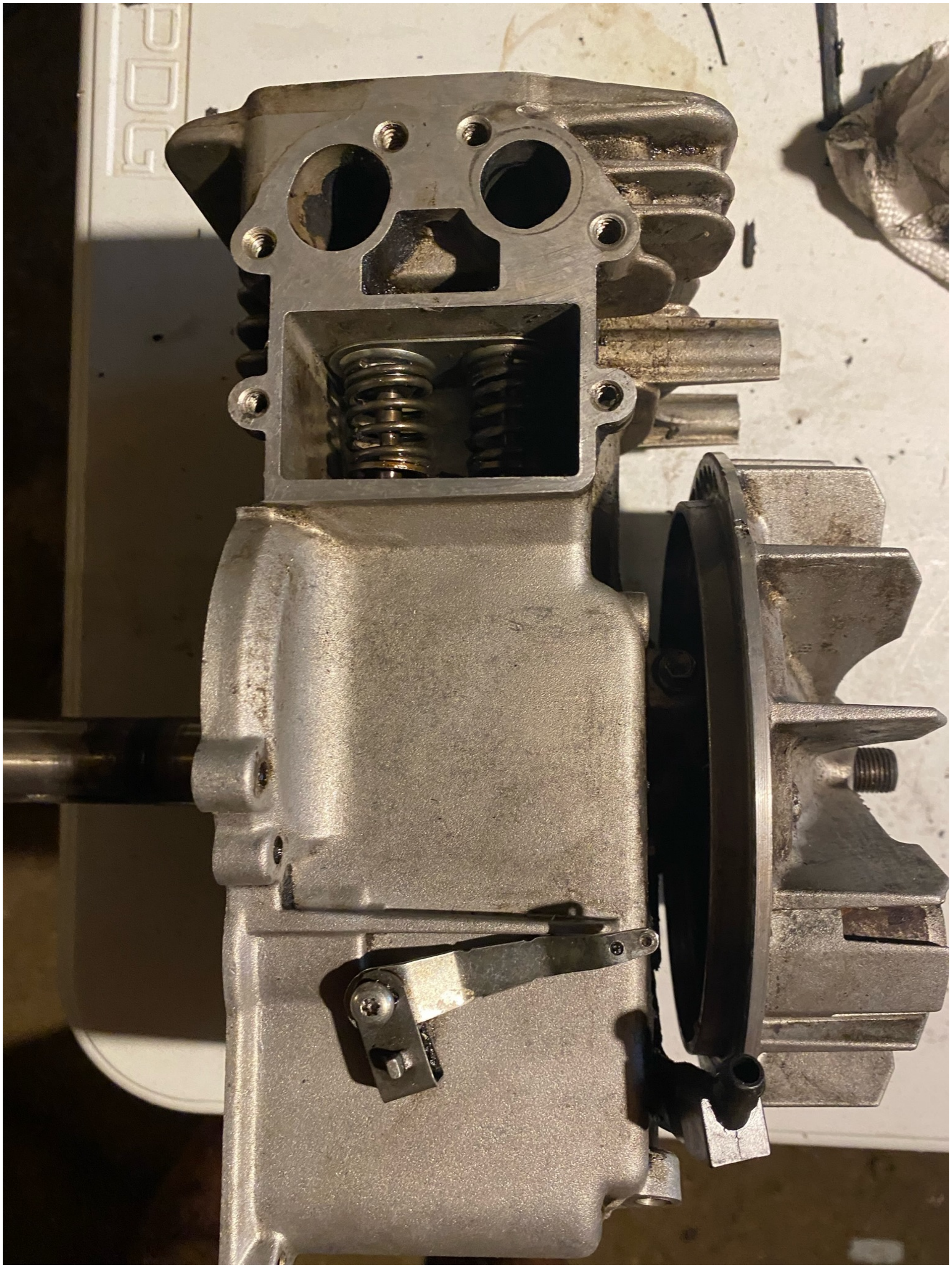
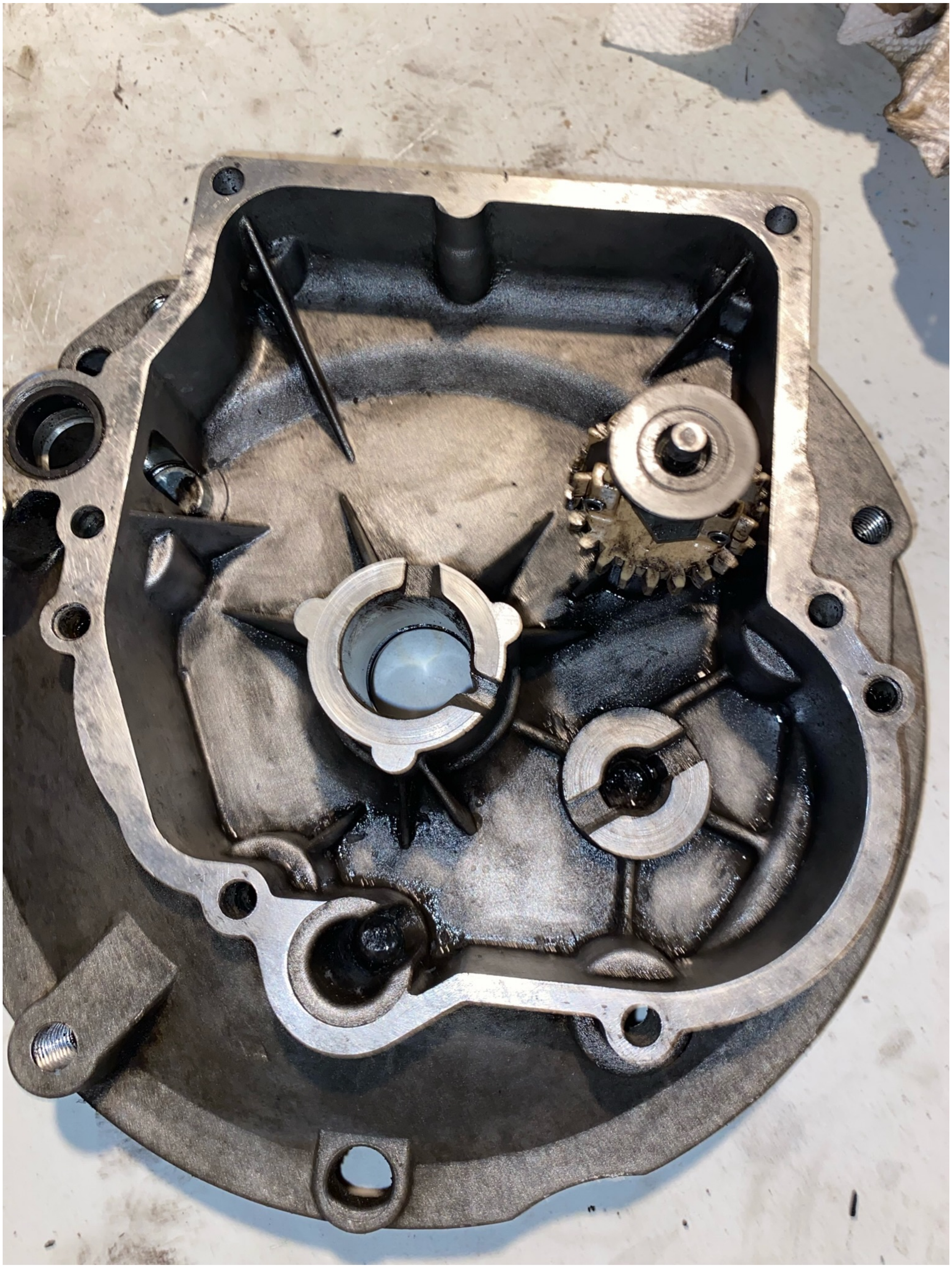
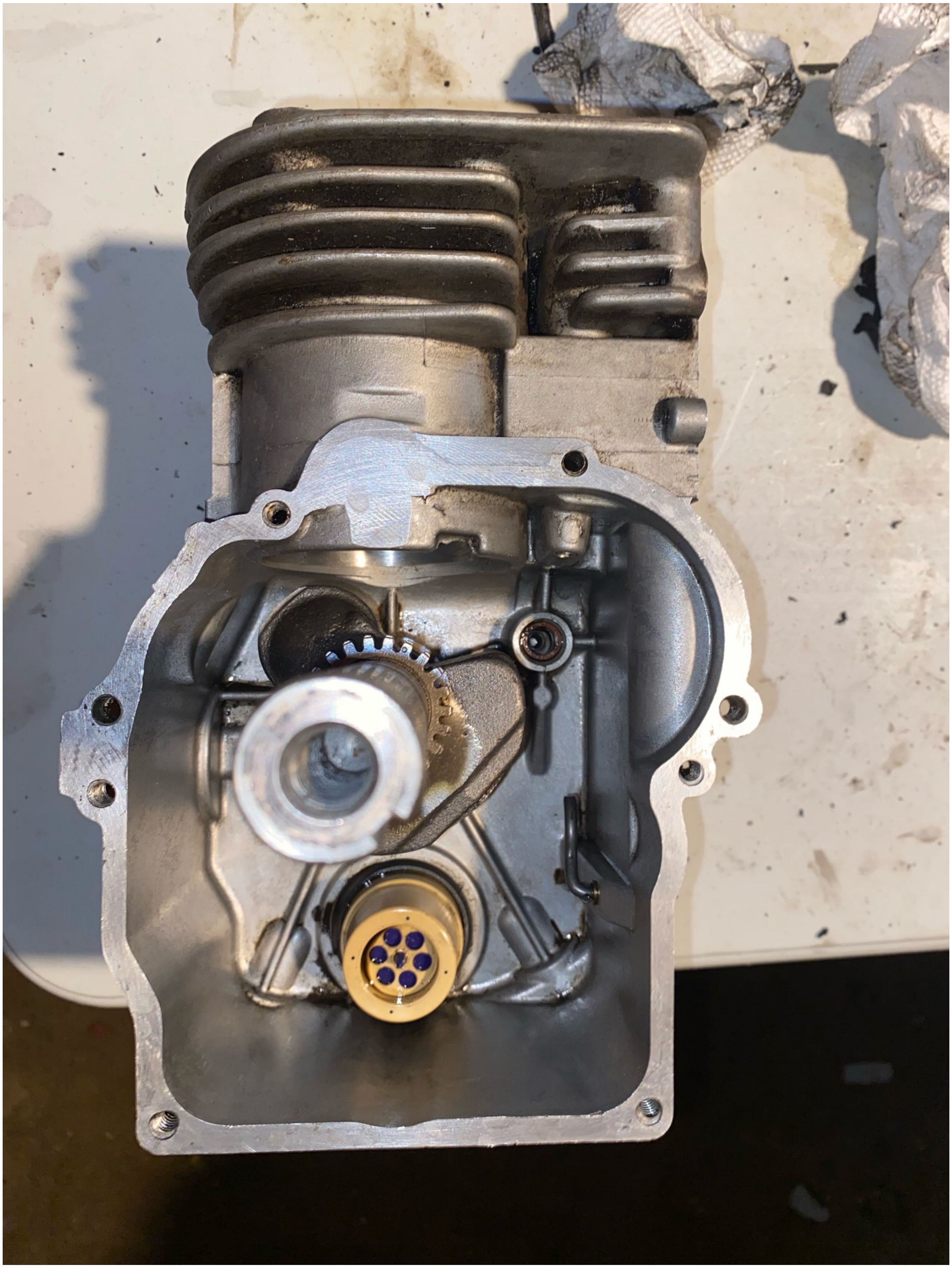
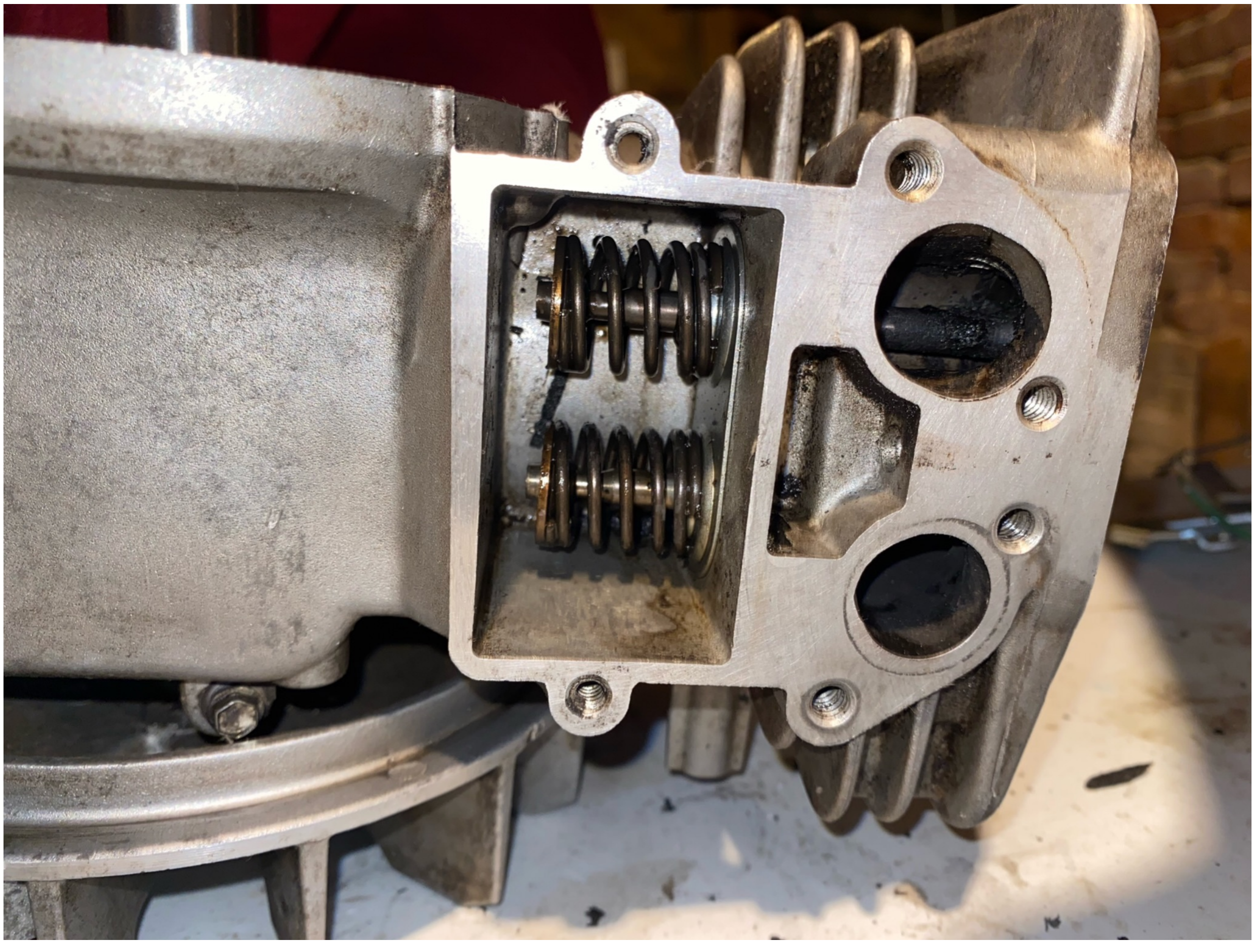
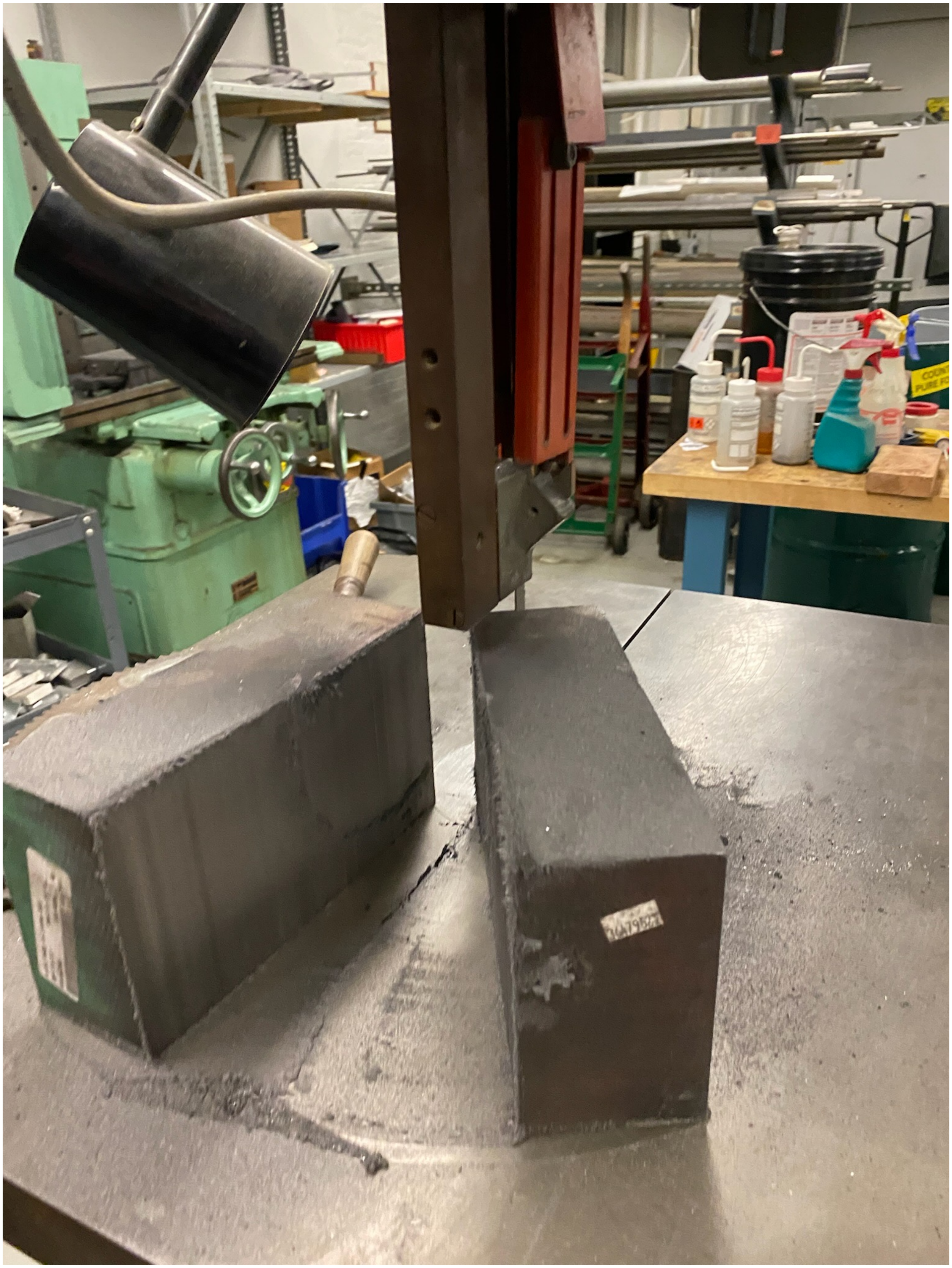




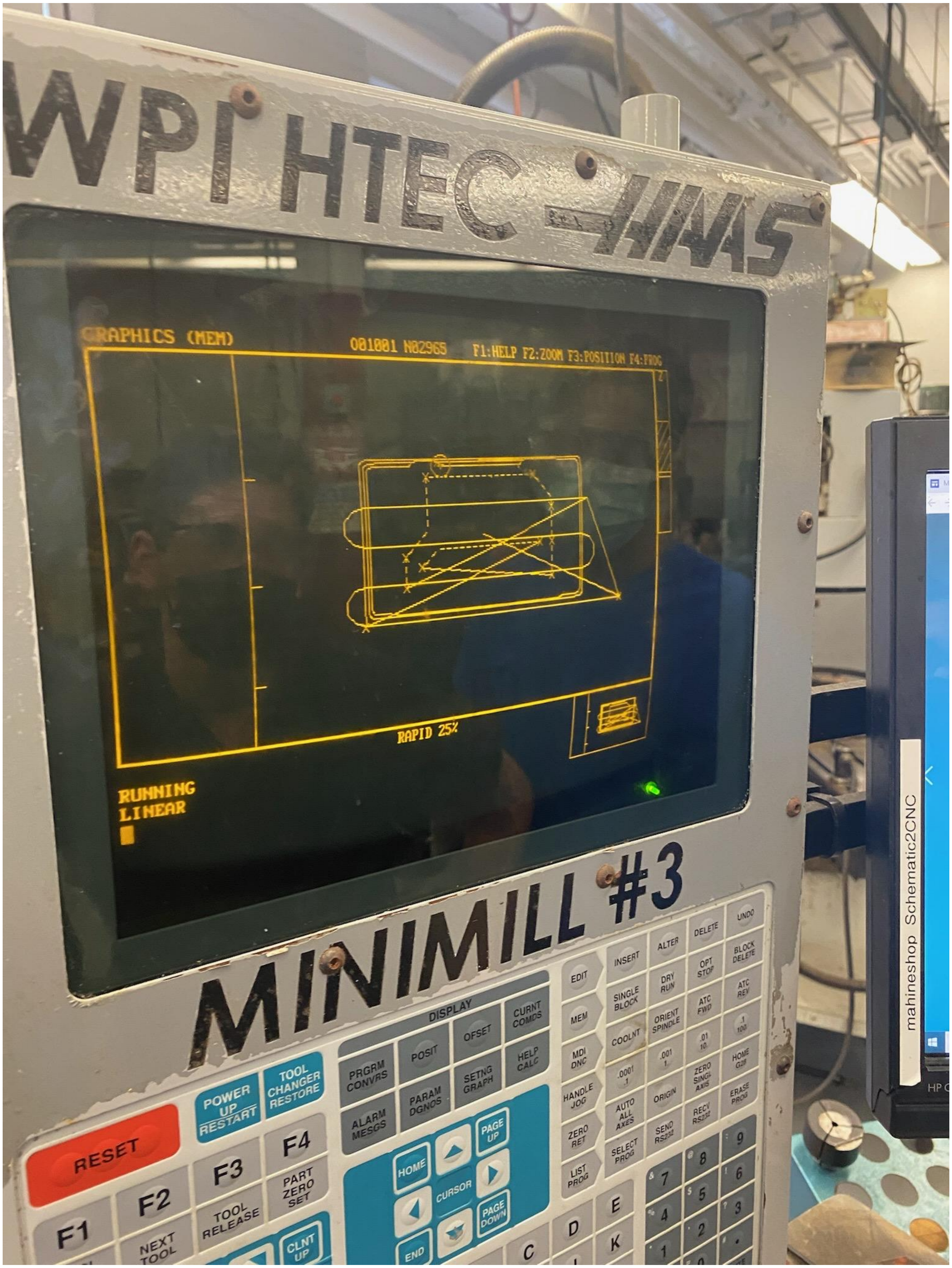







HAAS
WARNING


THIS MACHINE IS AUTOMATICALLY CONTROLLED AND MAY START AT ANY TIME.
THIS MACHINE CAN CAUSE SEVERE BODILY INJURY !!
DO NOT OPERATE WITH THE DOOR OPEN
DO NOT OPERATE WITHOUT PROPER TRAINING.
ALWAYS WEAR SAFETY GOGGLES.
NEVER PLACE YOUR HAND ON THE TOOL IN THE SPINDLE AND PRESS ATC FWD, ATC REV, NEXT TOOL, OR CAUSE A TOOL CHANGE CYCLE. THE TOOL CHANGER WILL MOVE IN AND CRUSH YOUR HAND !!!.
TO AVOID TOOL CHANGER DAMAGE, ENSURE THAT TOOLS ARE PROPERLY ALIGNED WITH SPINDLE DRIVE LUGS WHEN LOADING TOOLS !!!
WARNING !!! WARNING !!! WARNING !!!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O01001 N02965
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RAPID 25%
RUNNING
LINEAR
MINIMILL #3
RESET
POWER UP RESTART
TOOL CHANGER RESTORE
F1
F2
F3
F4
NEXT TOOL
TOOL RELEASE
PART ZERO SET
CLNT UP
DISPLAY
PRGRM CONVRS
POSIT
OFSET
CURNT COMDS
ALARM MESGS
PARAM DGNOS
SETNG GRAPH
HELP CALC
HOME
CURSOR
PAGE UP
PAGE DOWN
END
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ATC FWD
ATC REV
AUTO ALL AXES
ORIGIN
ZERO SINGL AXIS
HOME G28
SELECT PROG
SEND RS232
RECV RS232
ERASE PROG
mahineshop Schematic2CNC


WARNING !!! WARNING !!! WARNING !!!


THIS MACHINE IS AUTOMATICALLY CONTROLLED AND MAY START AT ANY TIME.
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ALWAYS WEAR SAFETY GOGGLES.
NEVER PLACE YOUR HAND ON THE TOOL IN THE SPINDLE AND PRESS ATC FWD, ATC REV, NEXT TOOL, OR CAUSE A TOOL CHANGE CYCLE. THE TOOL CHANGER WILL MOVE IN AND CRUSH YOUR HAND !!!
TO AVOID TOOL CHANGER DAMAGE, ENSURE THAT TOOLS ARE PROPERLY ALIGNED WITH SPINDLE DRIVE LUGS WHEN LOADING TOOLS !!!
WARNING !!! WARNING !!! WARNING !!!

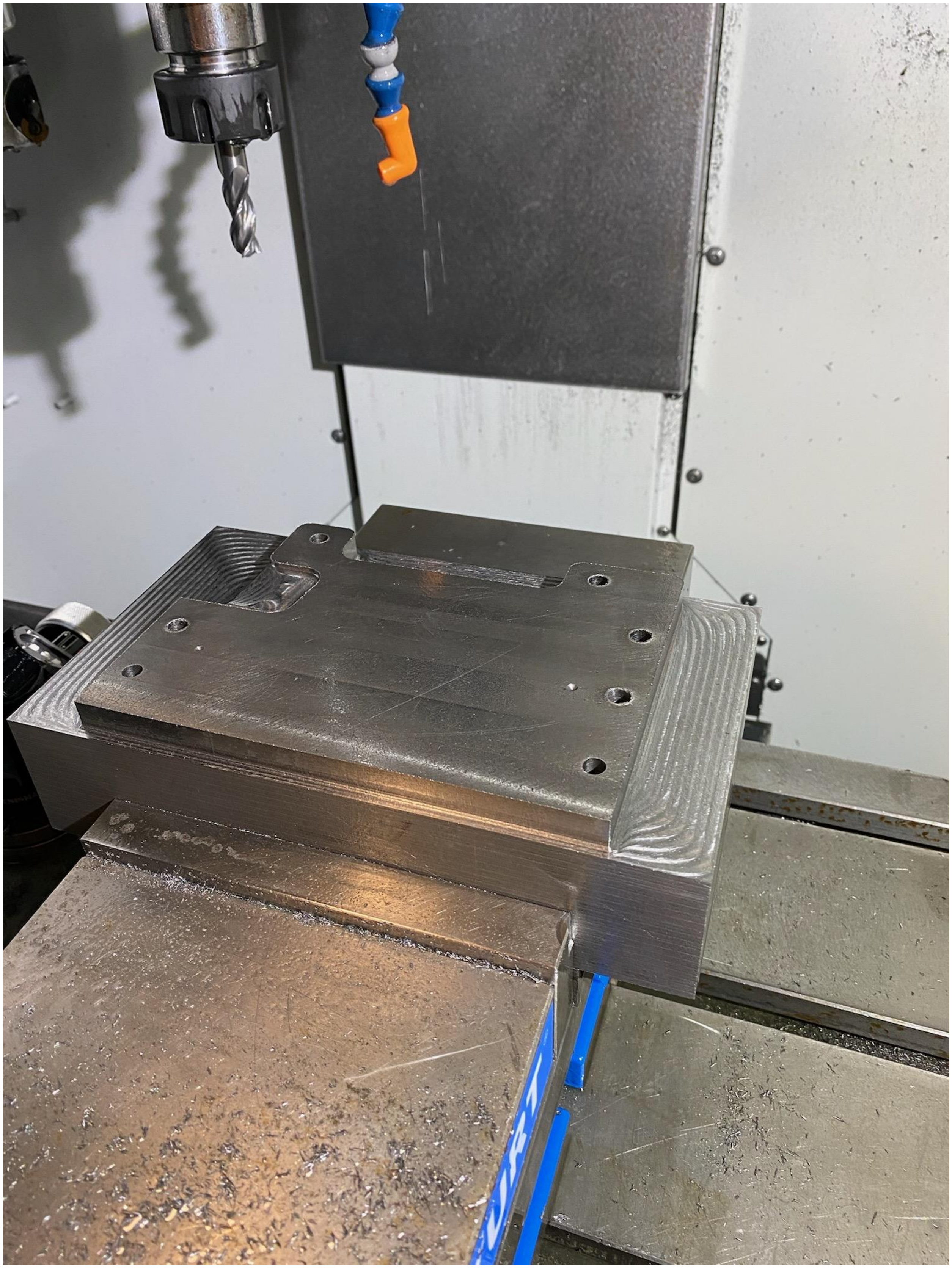

HAAS
WARNING
WPI
The Cape

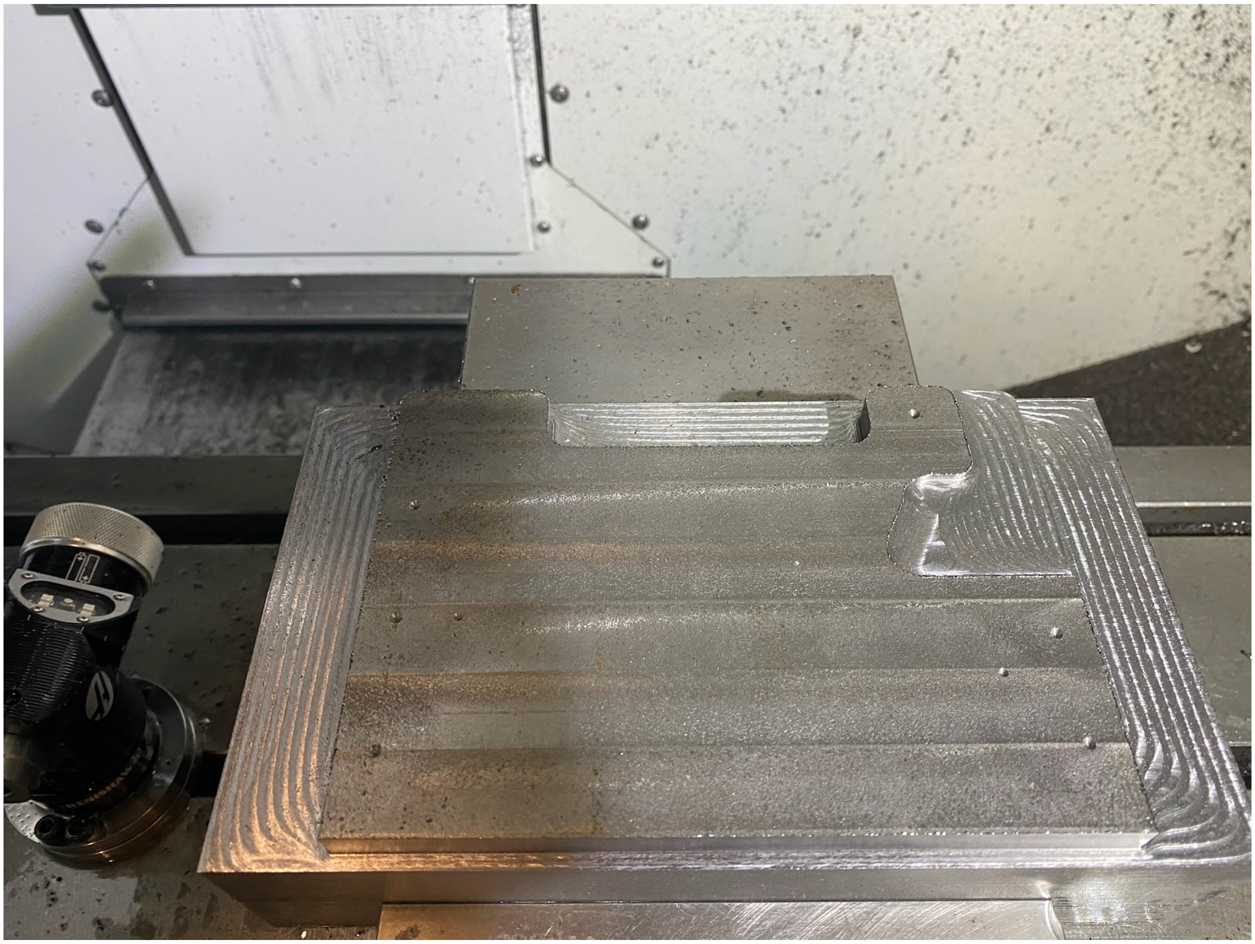

KURT
LONDON
adidas

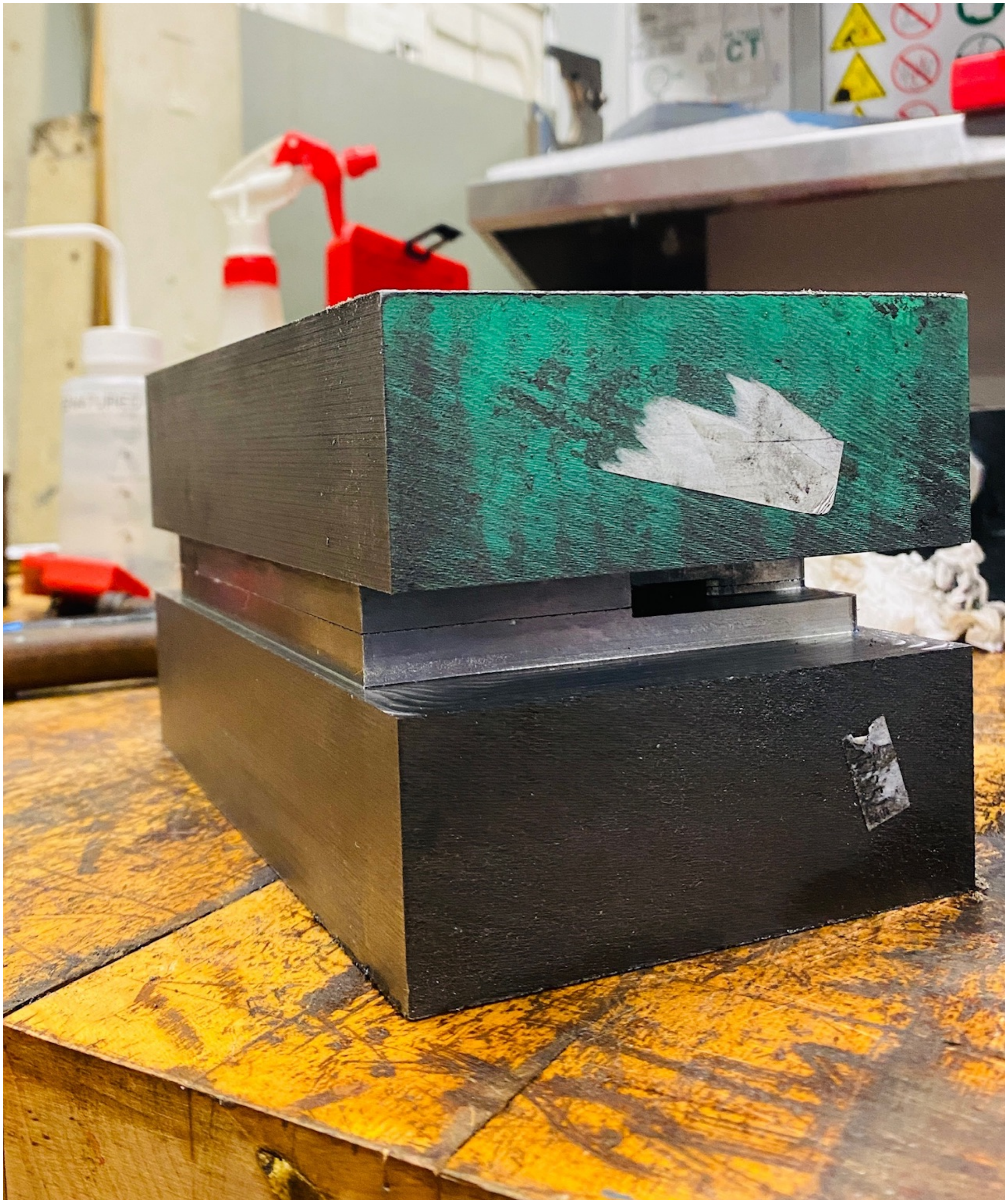

Taper Pipe Tap & Drill
Screw Thread Insert (STI) Tap & Drill
Metric Thread Form Tap & Drill
Plumbing & Heating
Since 1947


QUILL FEED
KURT
Manual Mill 1


KURT



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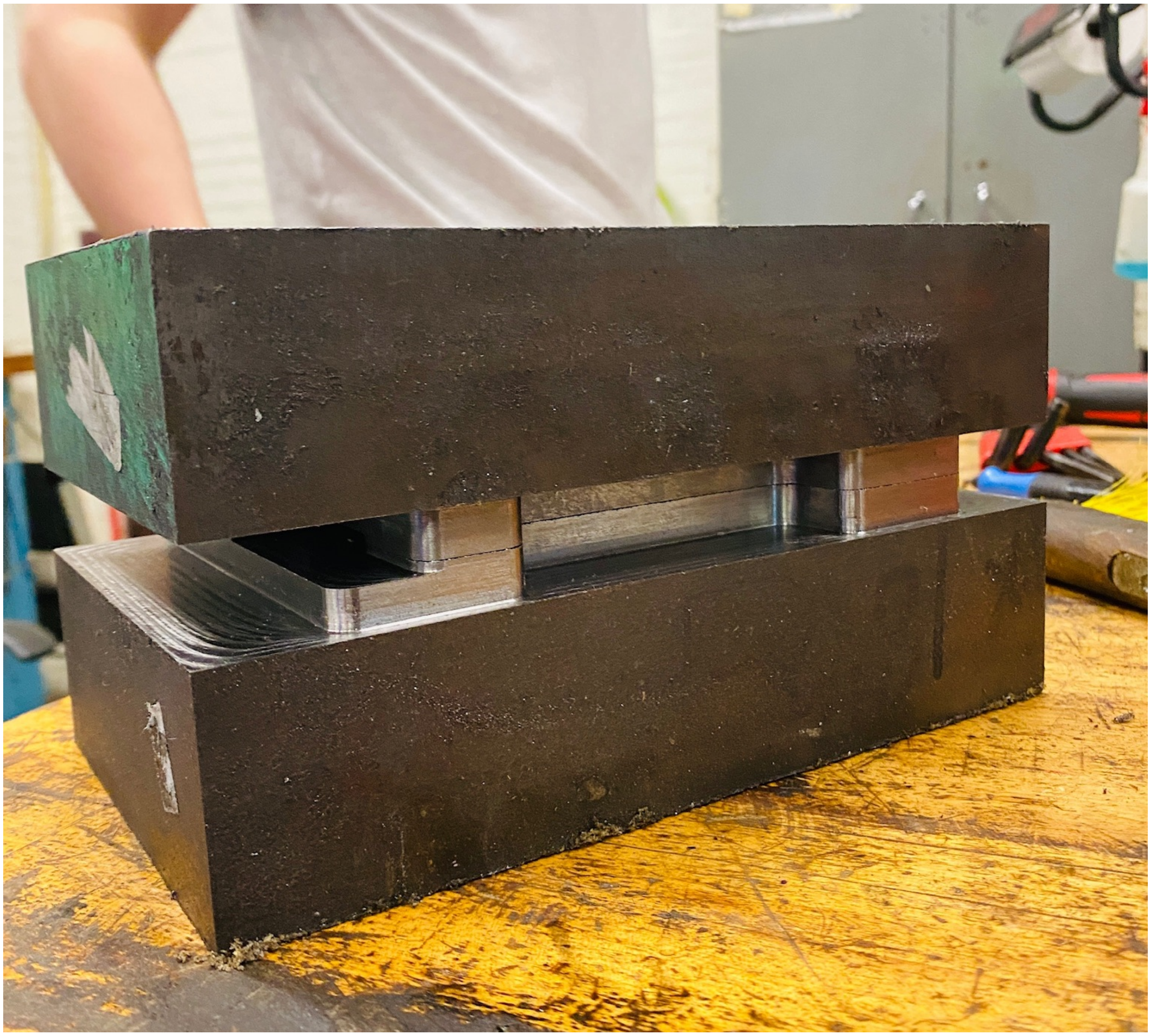

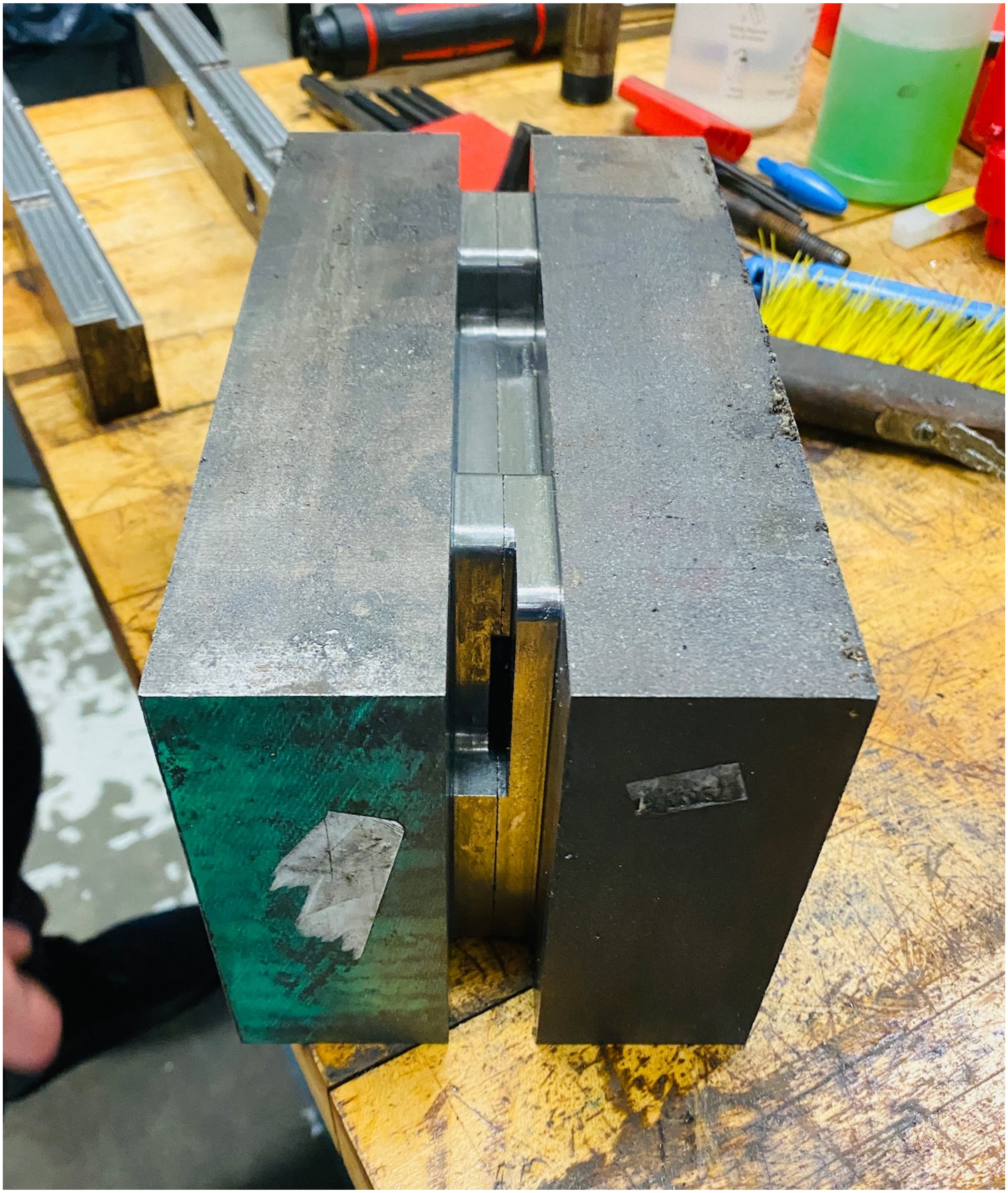


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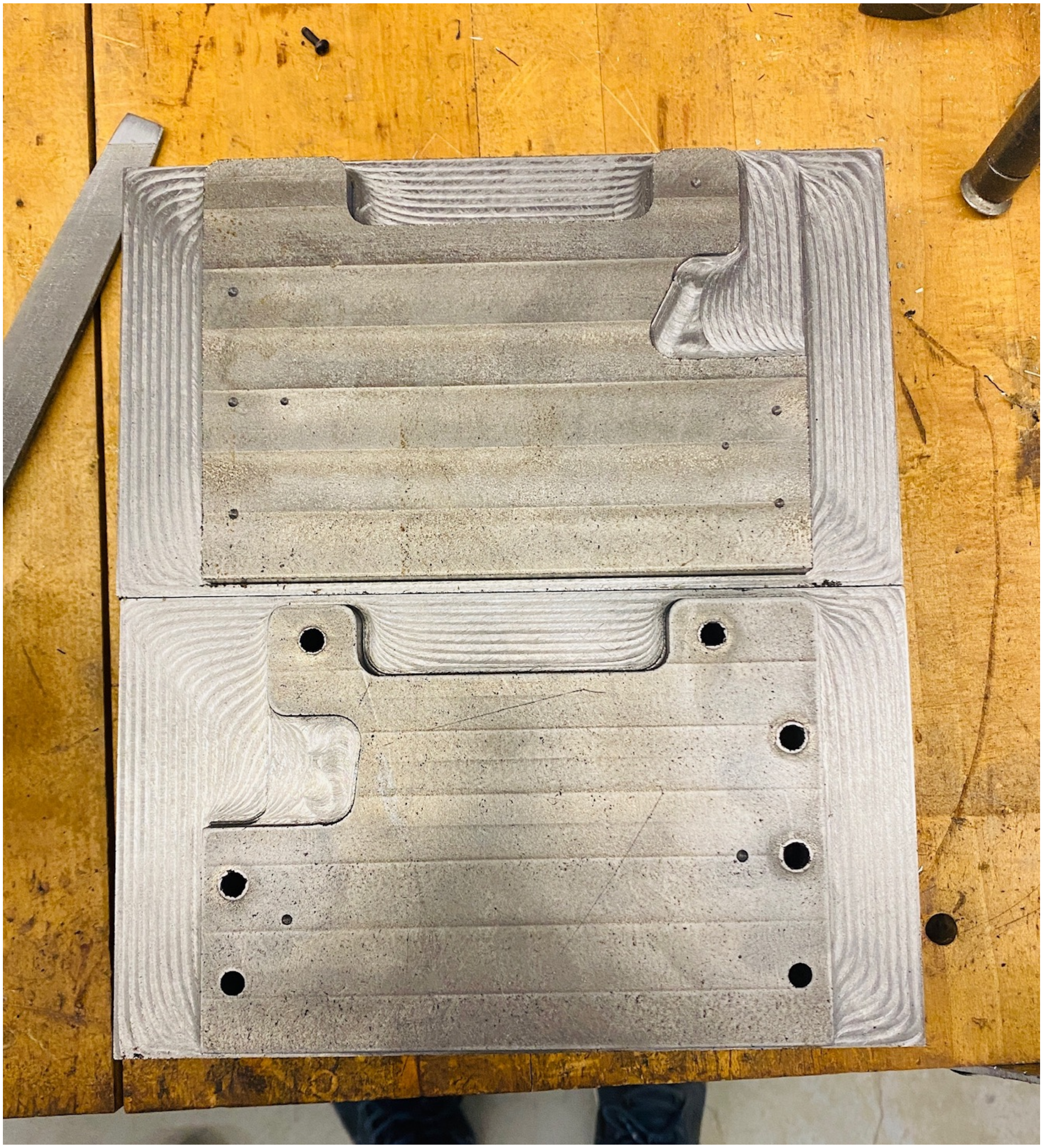


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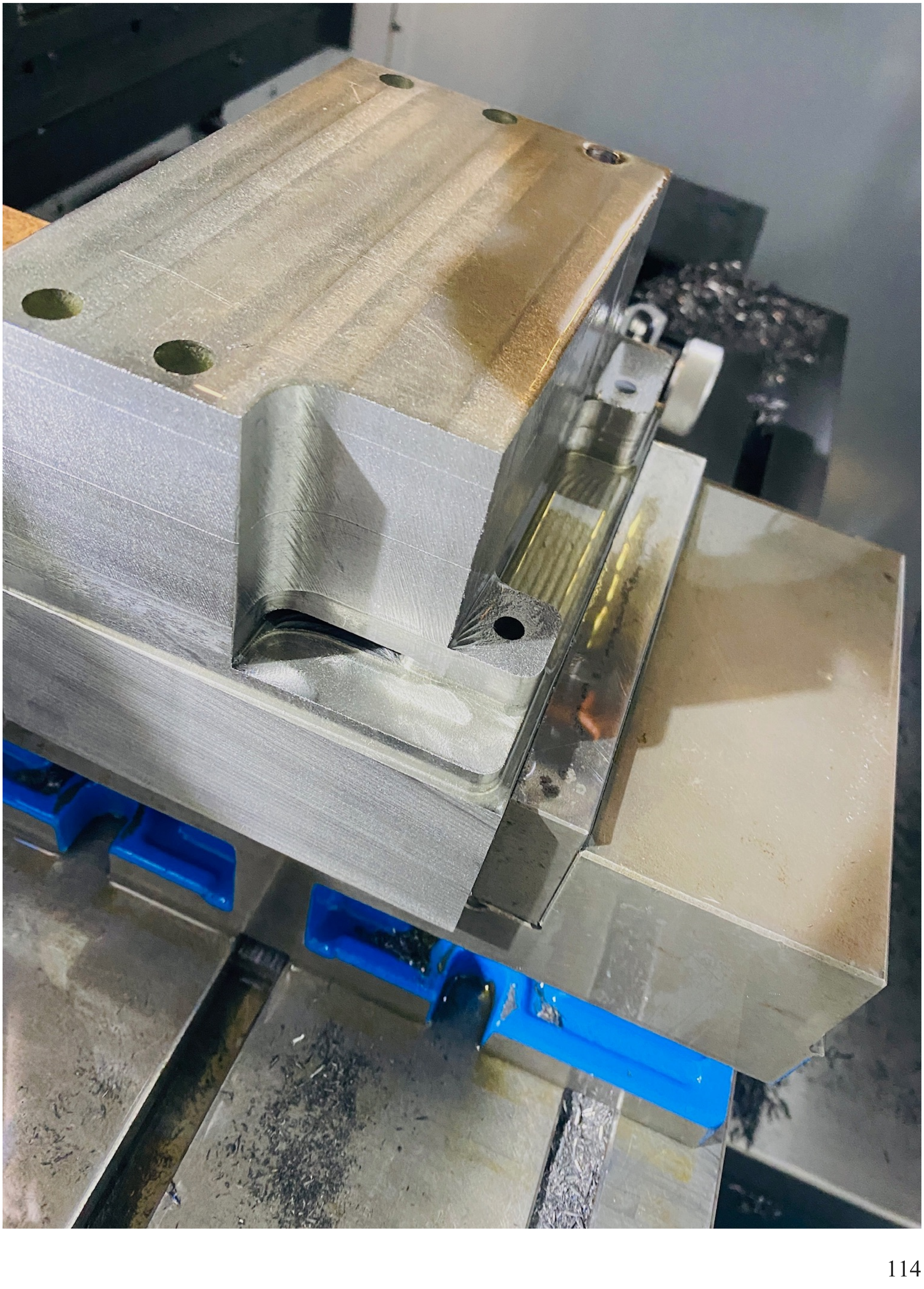

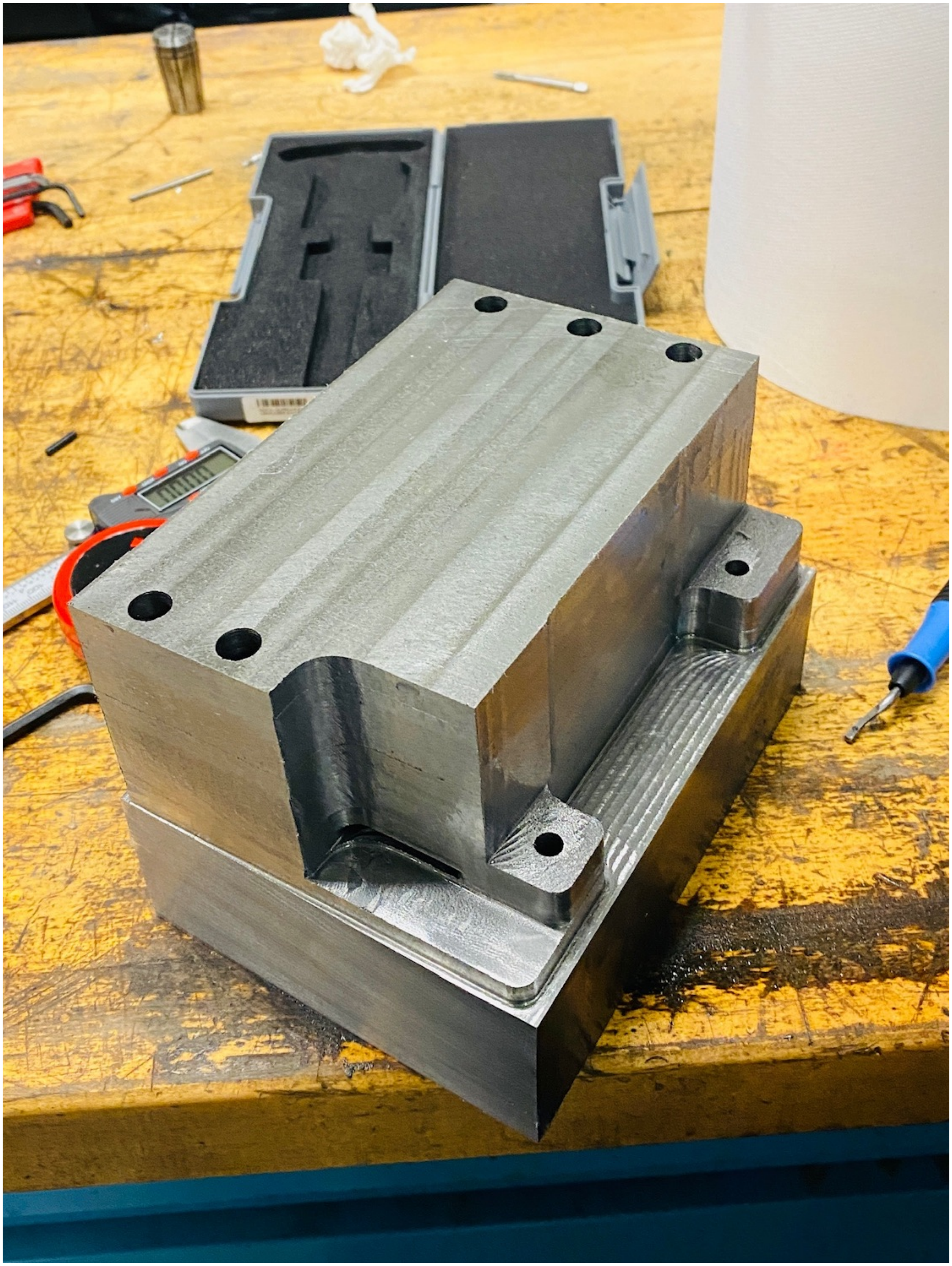

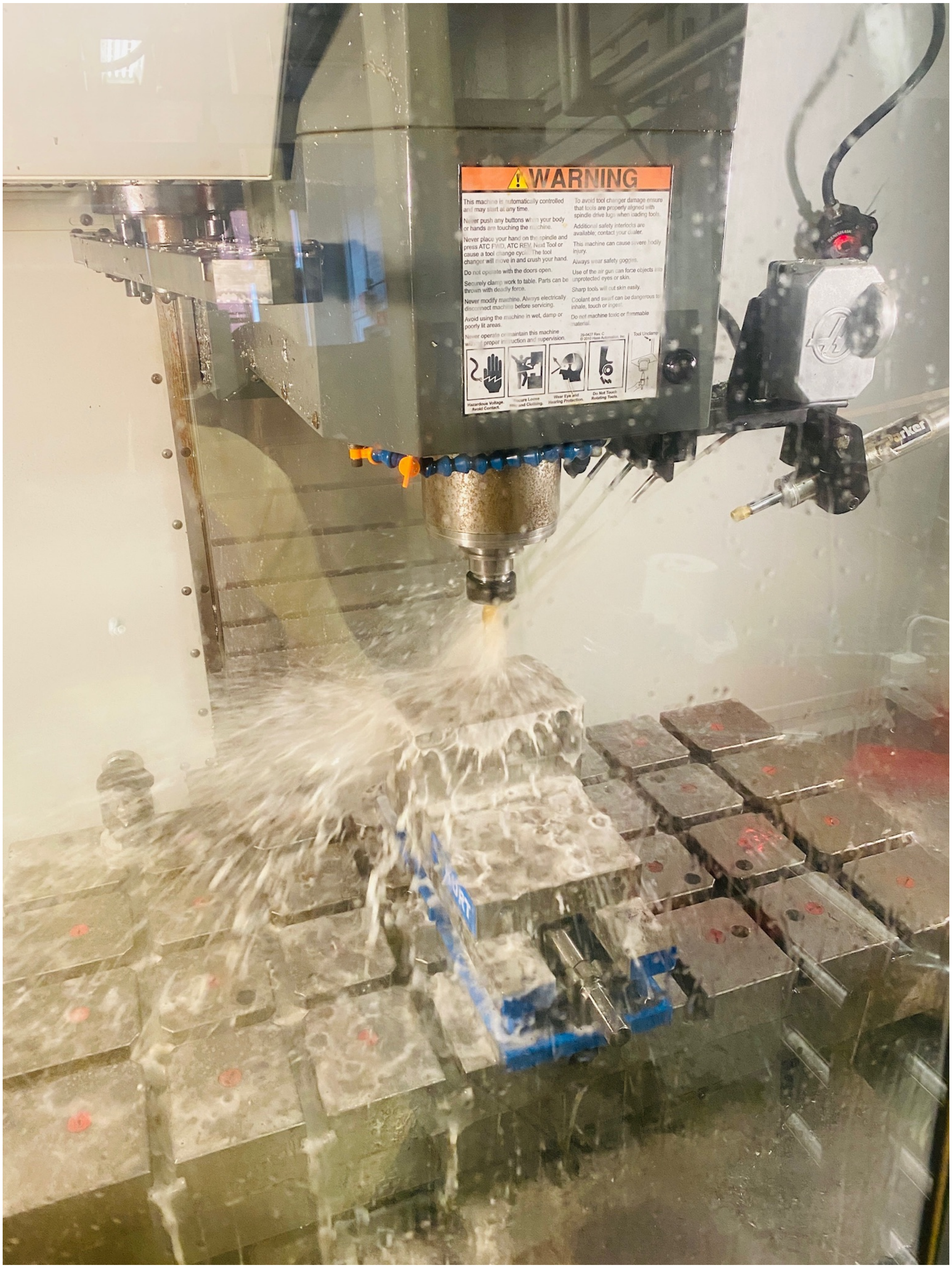
WARNING


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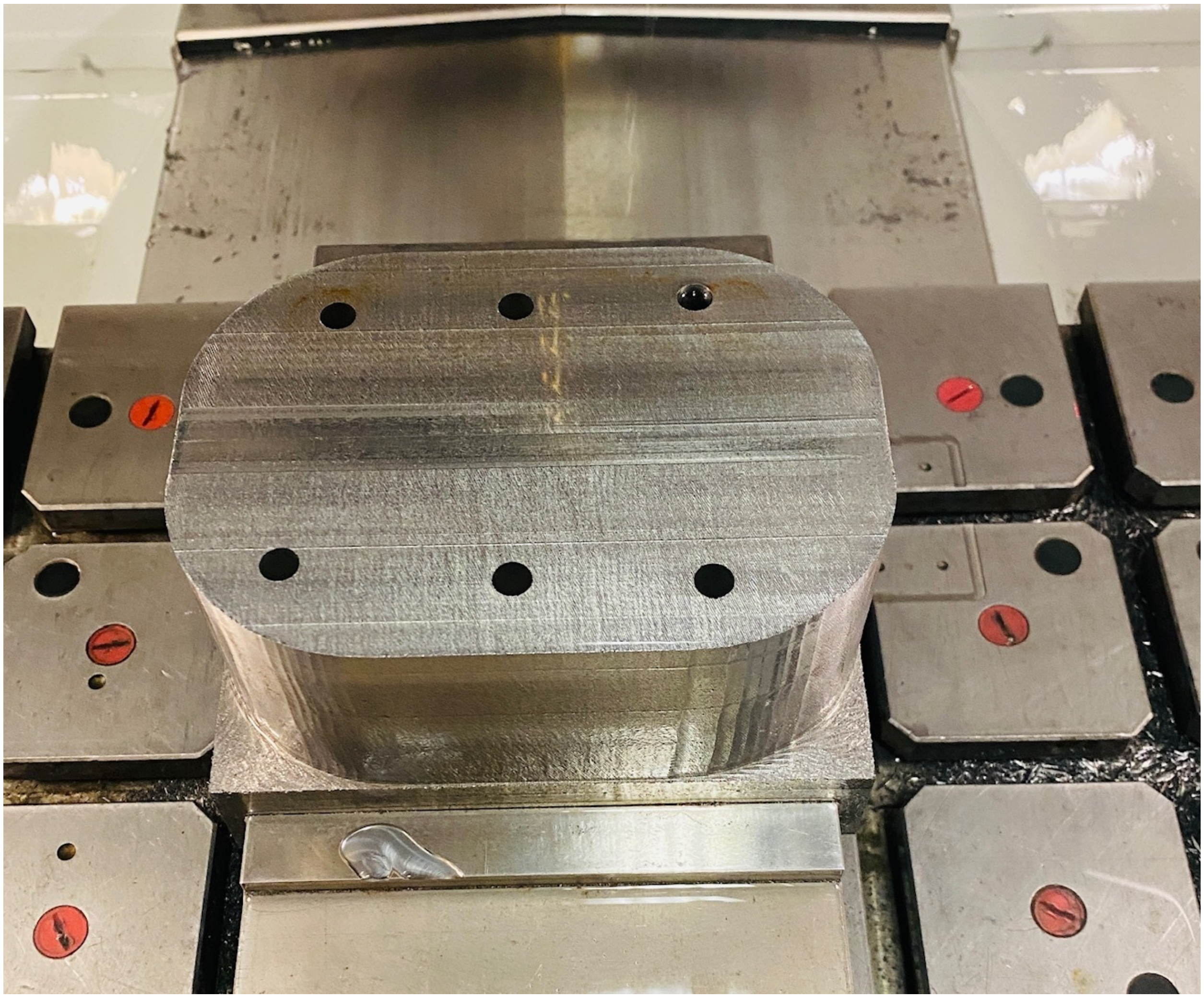
WARNING
This machine is automatically controlled and may start at any time.
Never push any buttons when your body or hands are touching the machine.
Never place your hand on the spindle and press ATC FWD, ATC REV, Next Tool or cause a tool change cycle. The tool changer will move in and crush your hand.
Do not operate with the doors open.
Securely clamp work to table. Parts can be thrown with deadly force.
Never modify machine. Always electrically disconnect machine before servicing.
Avoid using the machine in wet, damp or poorly lit areas.
Never operate or maintain this machine without proper instruction and supervision.
To avoid tool changer damage ensure that tools are properly aligned with spindle drive lugs when loading tools.
Additional safety interlocks are available; contact your dealer.
This machine can cause severe bodily injury.
Always wear safety goggles.
Use of the air gun can force objects into unprotected eyes or skin.
Sharp tools will cut skin easily.
Coolant and swarf can be dangerous to inhale, touch or ingest.
Do not machine toxic or flammable material.
29-0427 Rev. C
© 2010 Haas Automation, Inc.
Tool Unclamp
Hazardous Voltage. Avoid Contact.
Secure Loose Hair and Clothing.
Wear Eye and Hearing Protection.
Do Not Touch Rotating Tools.

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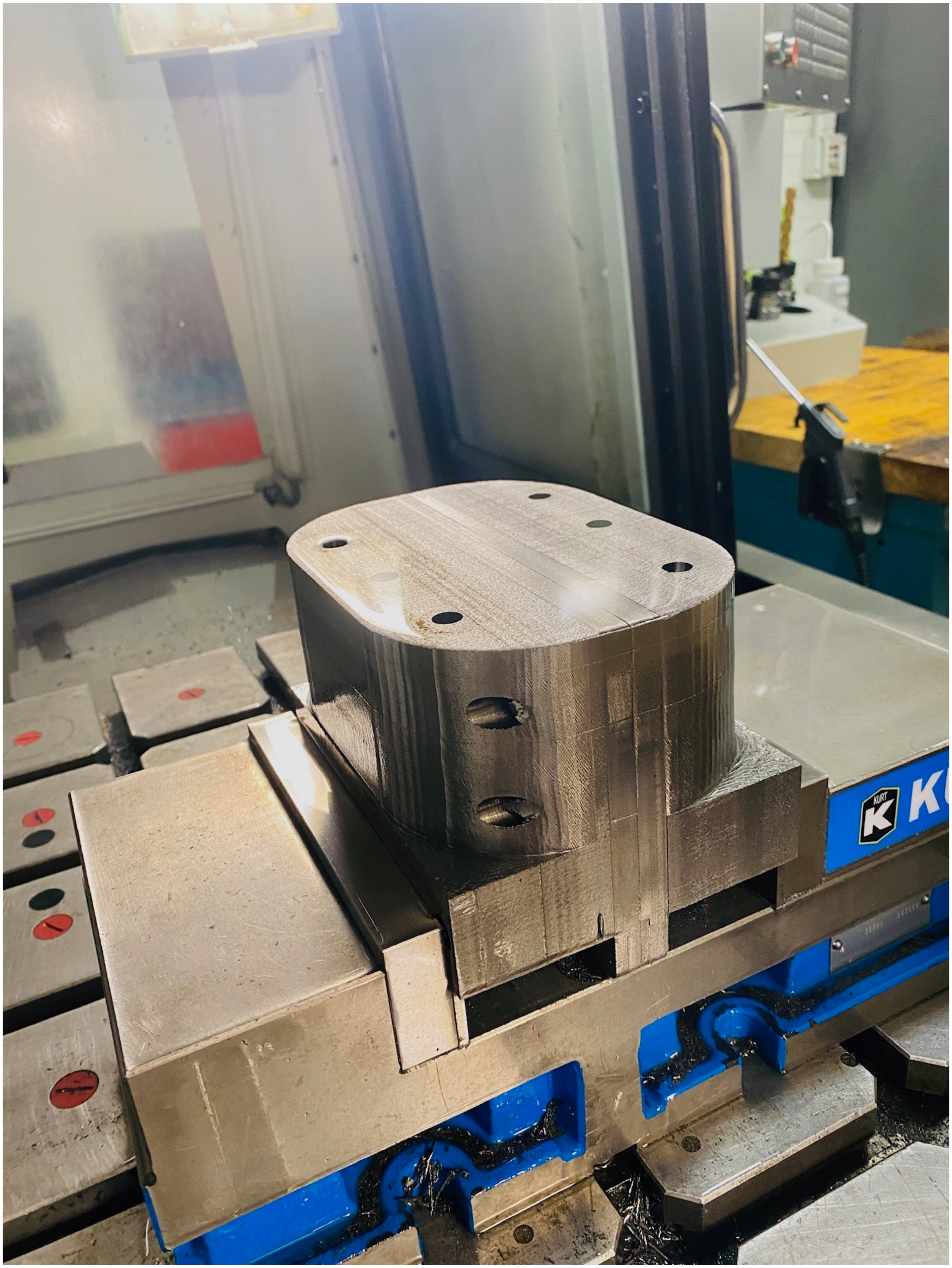

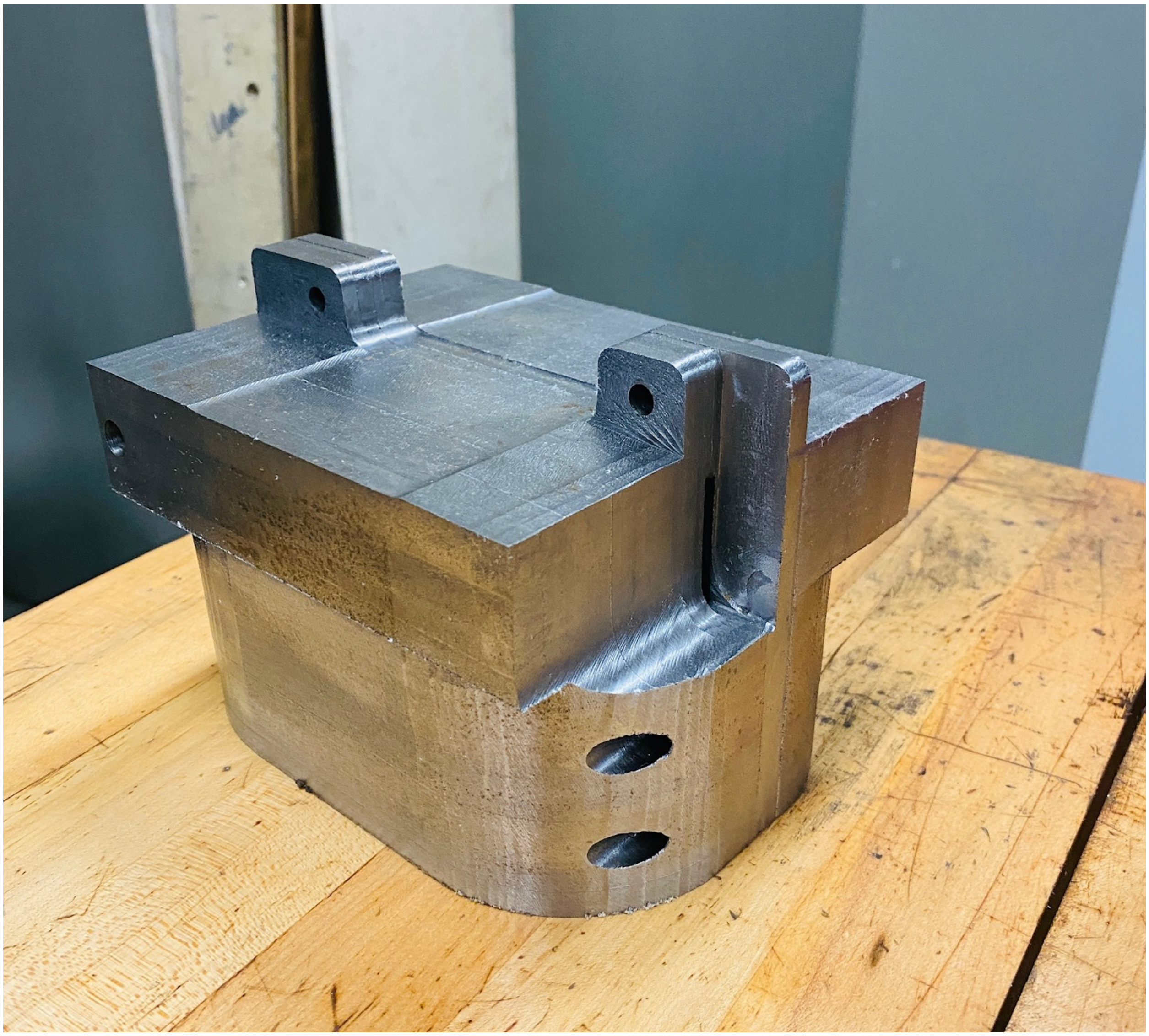

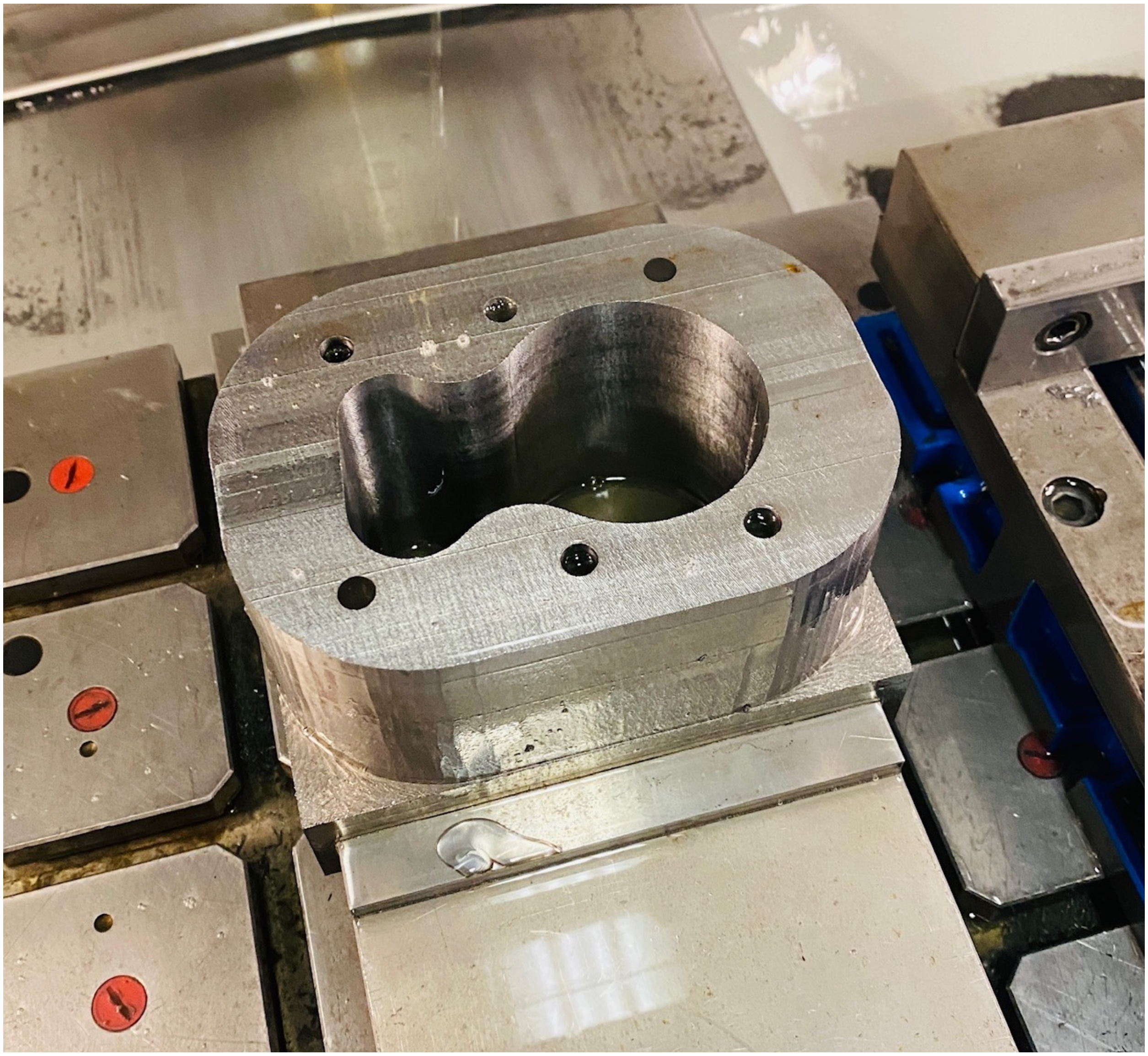

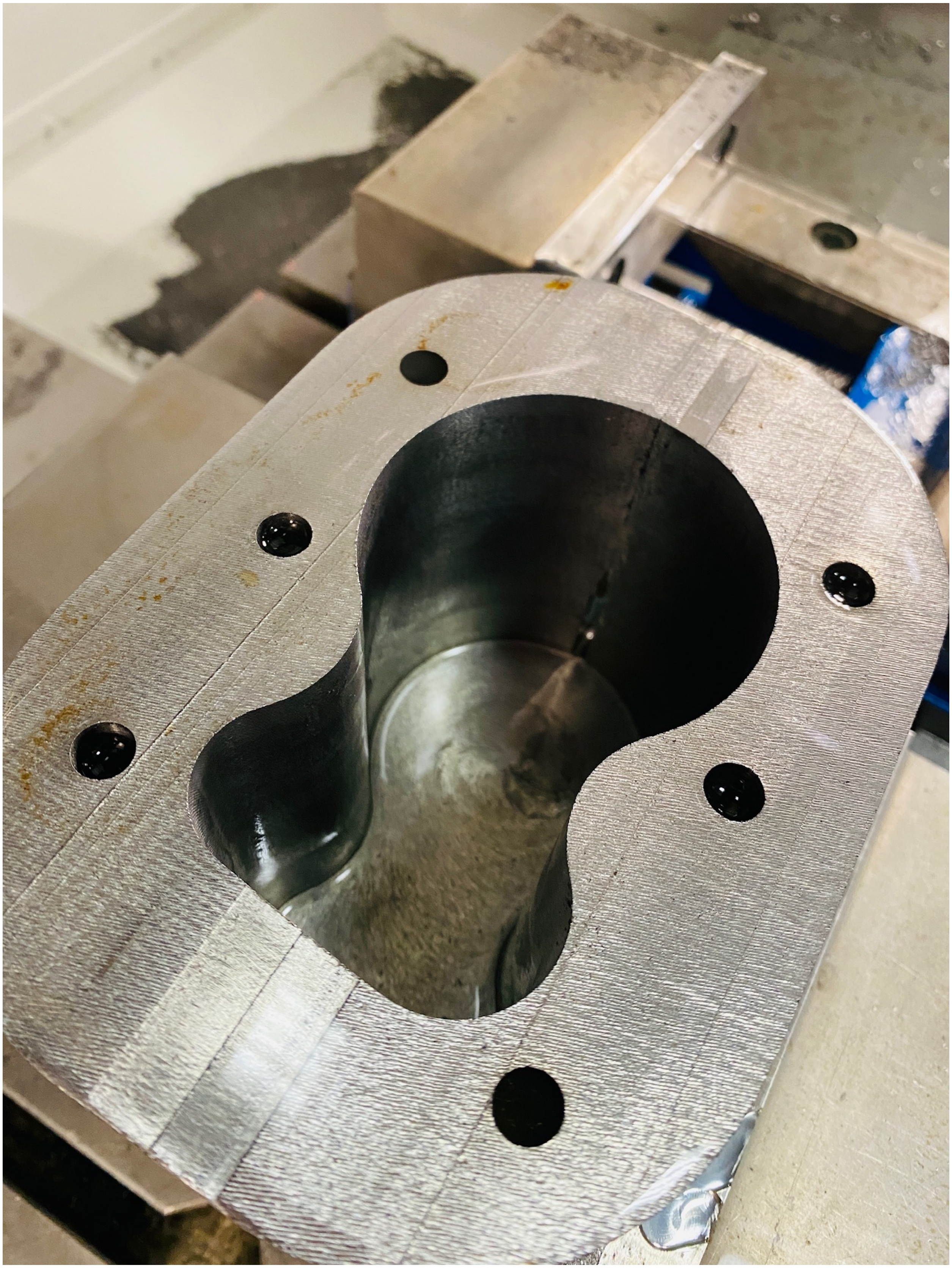

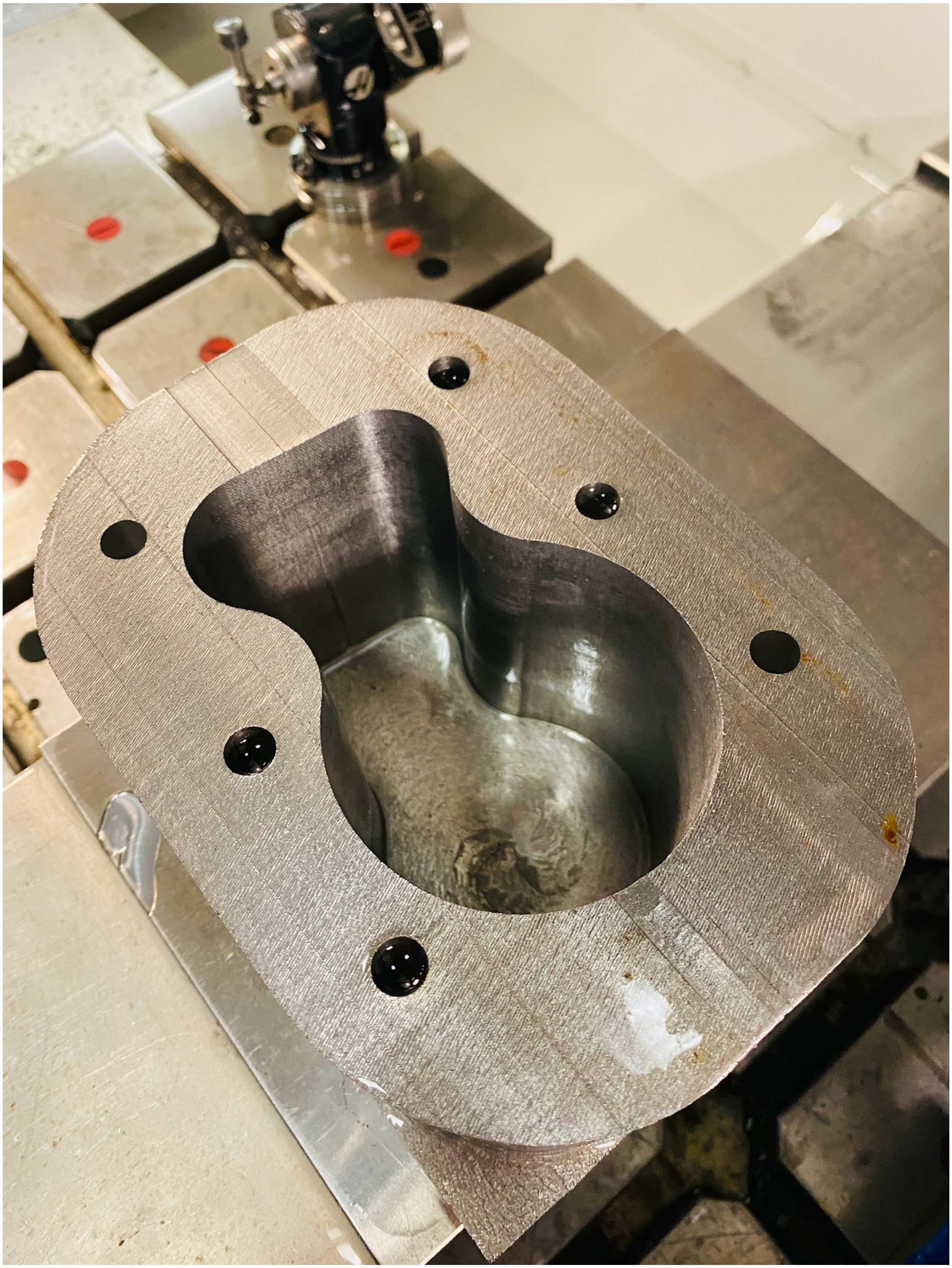

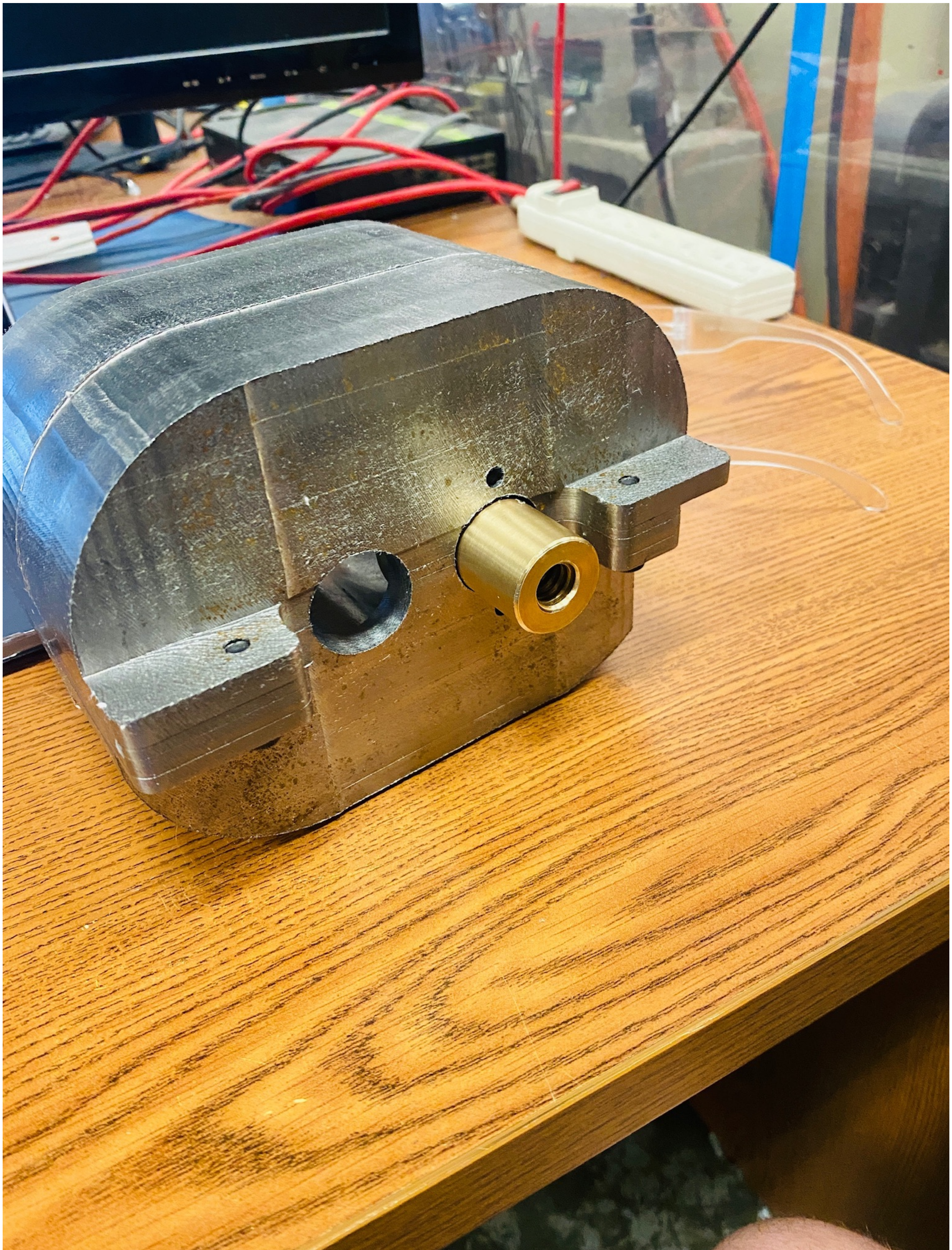

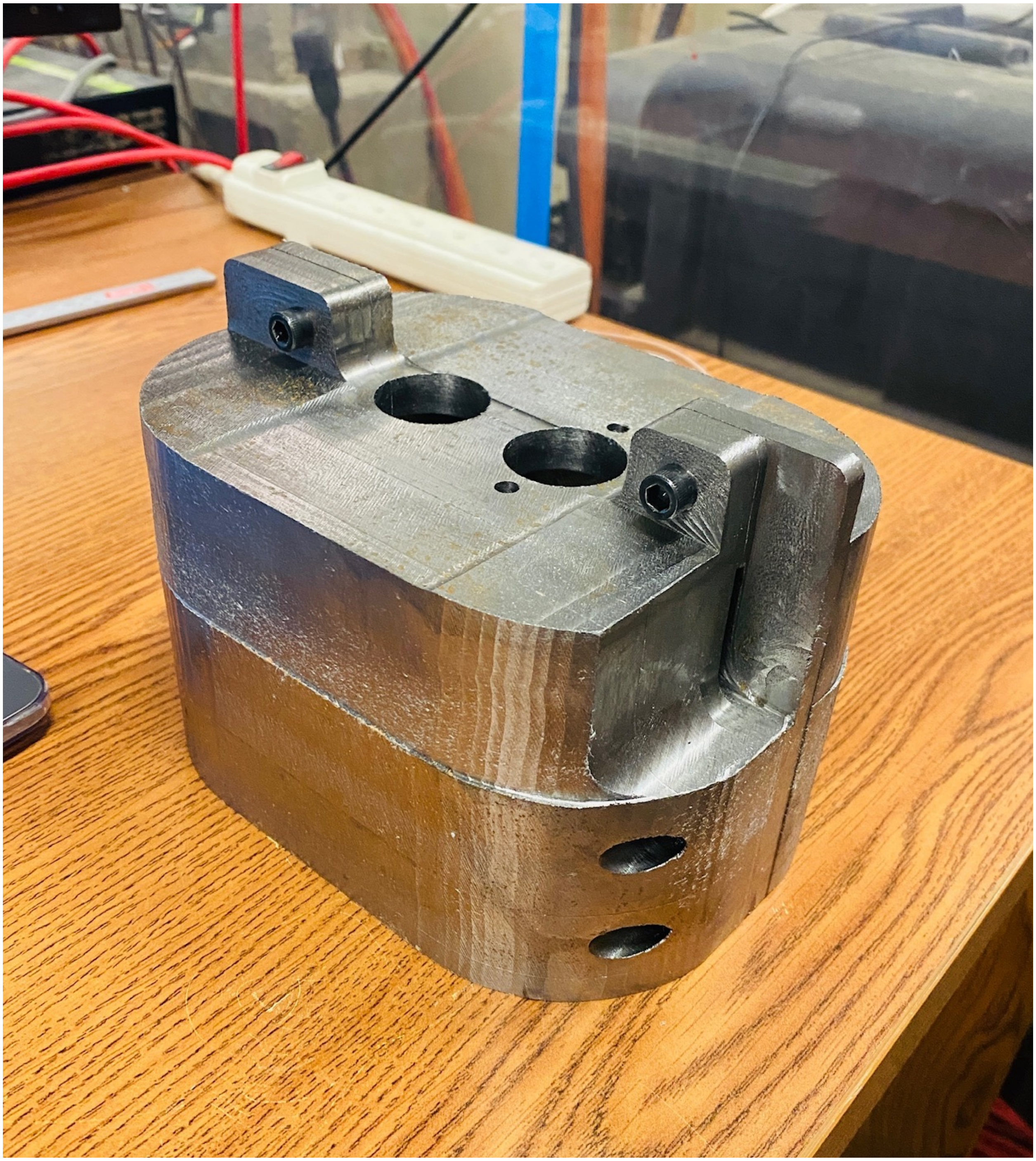

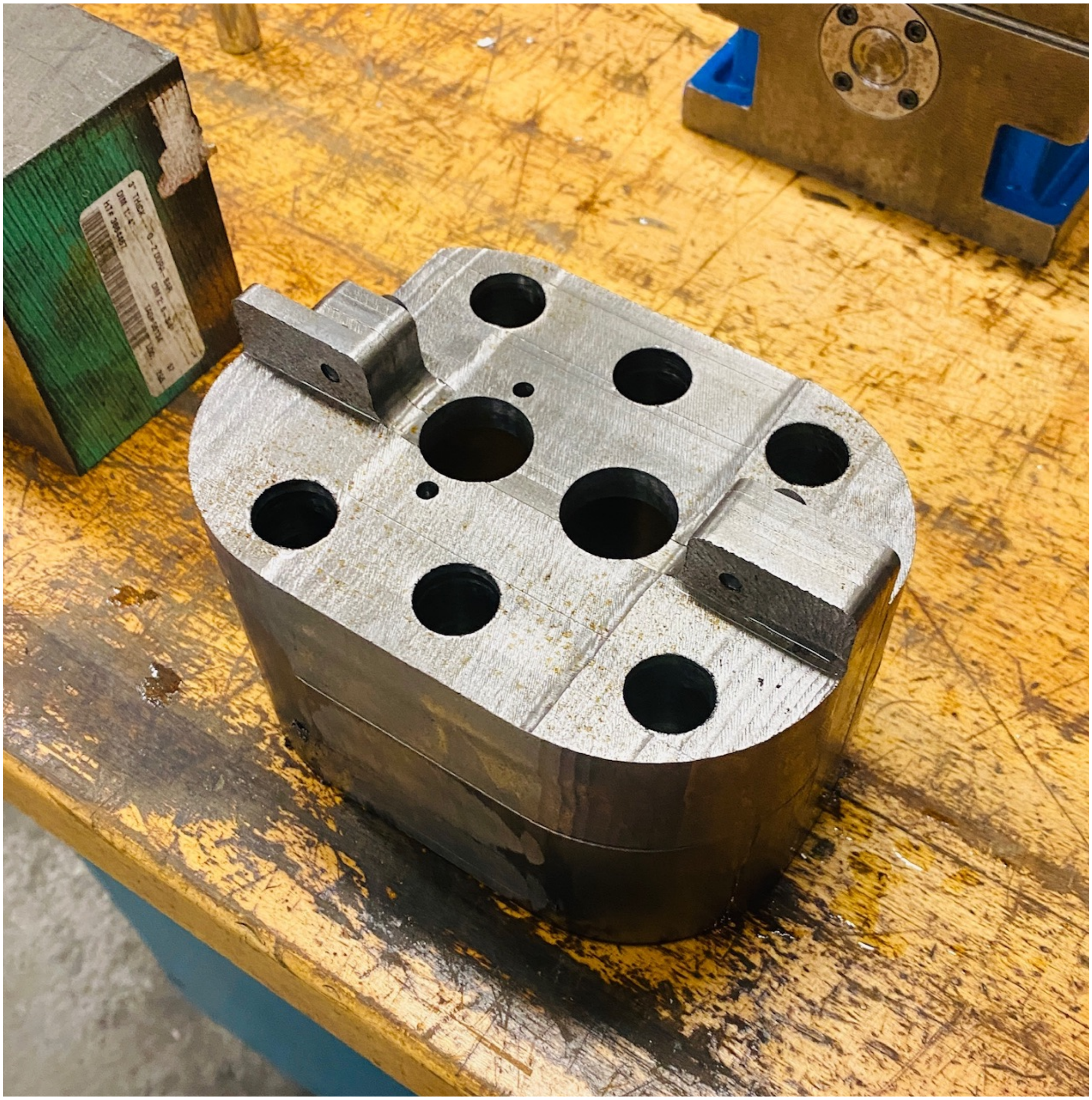

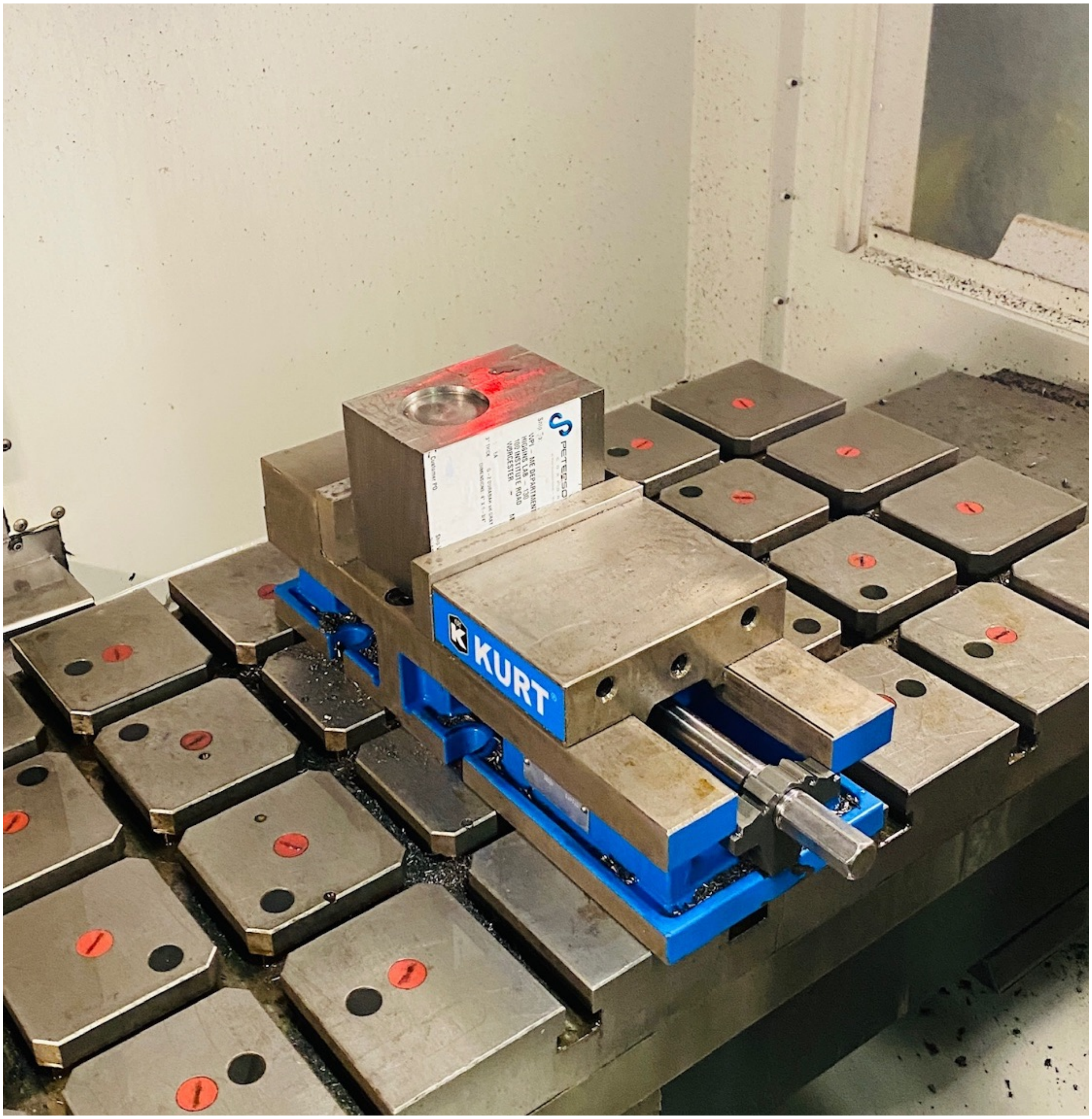
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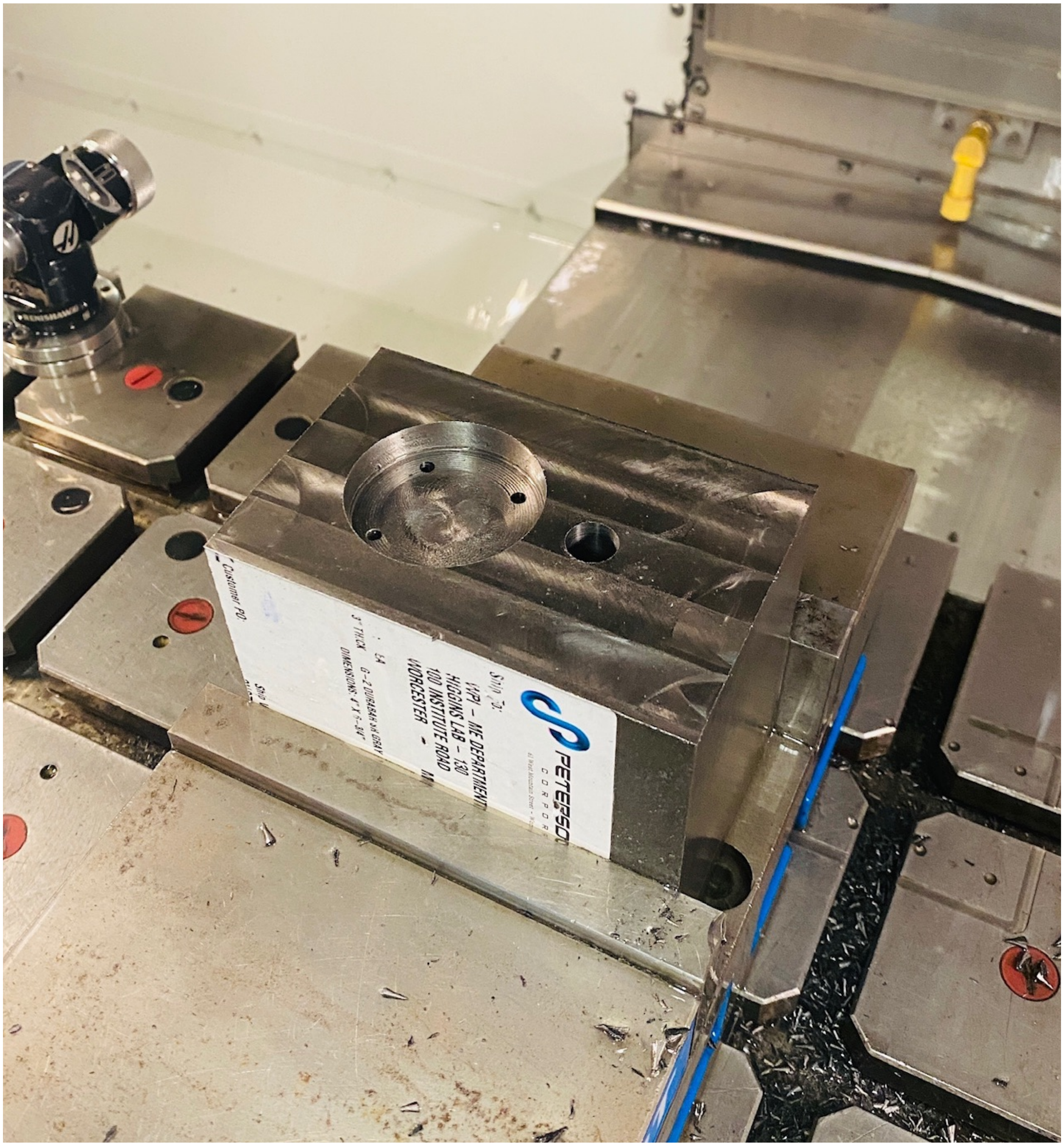
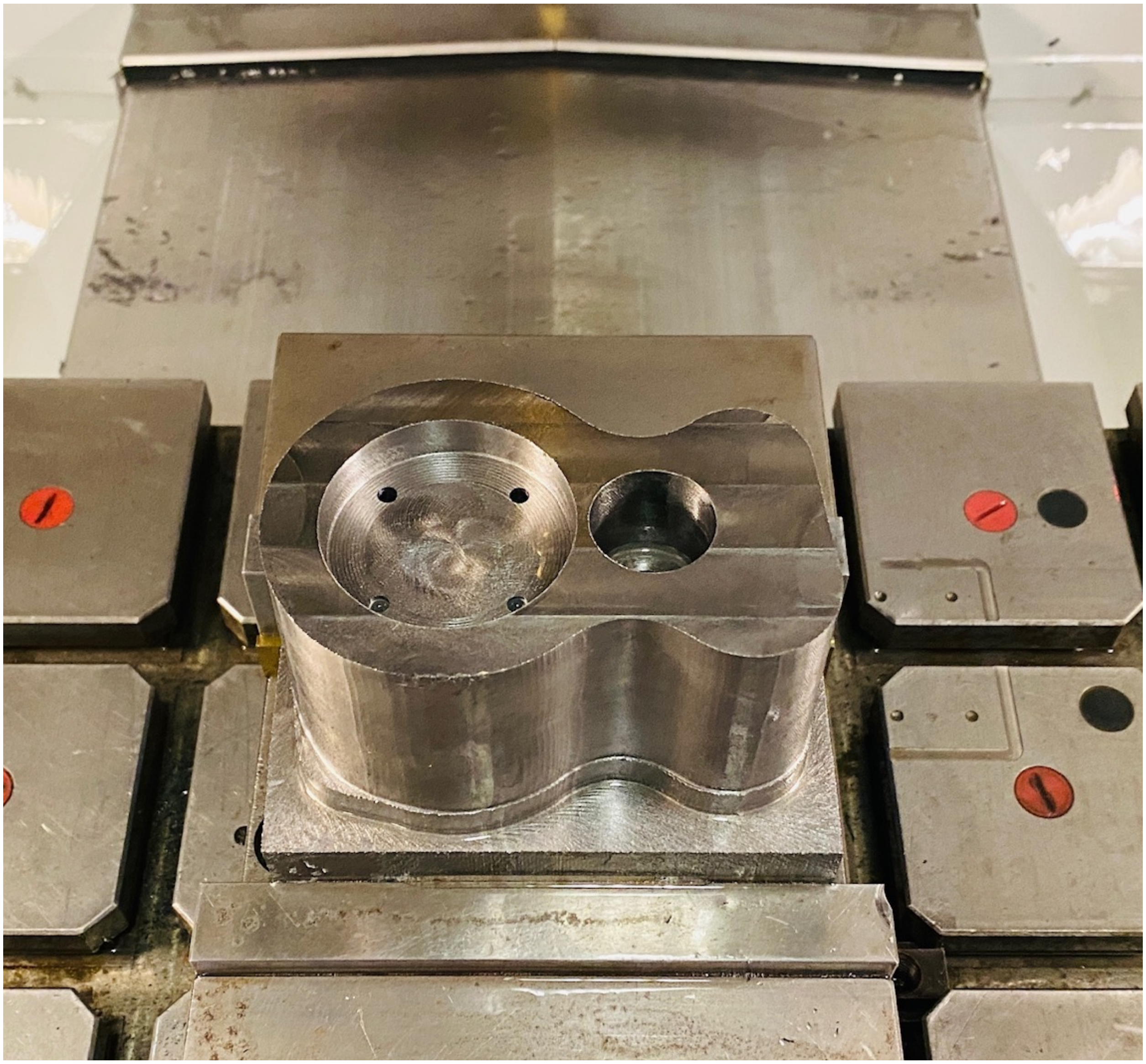
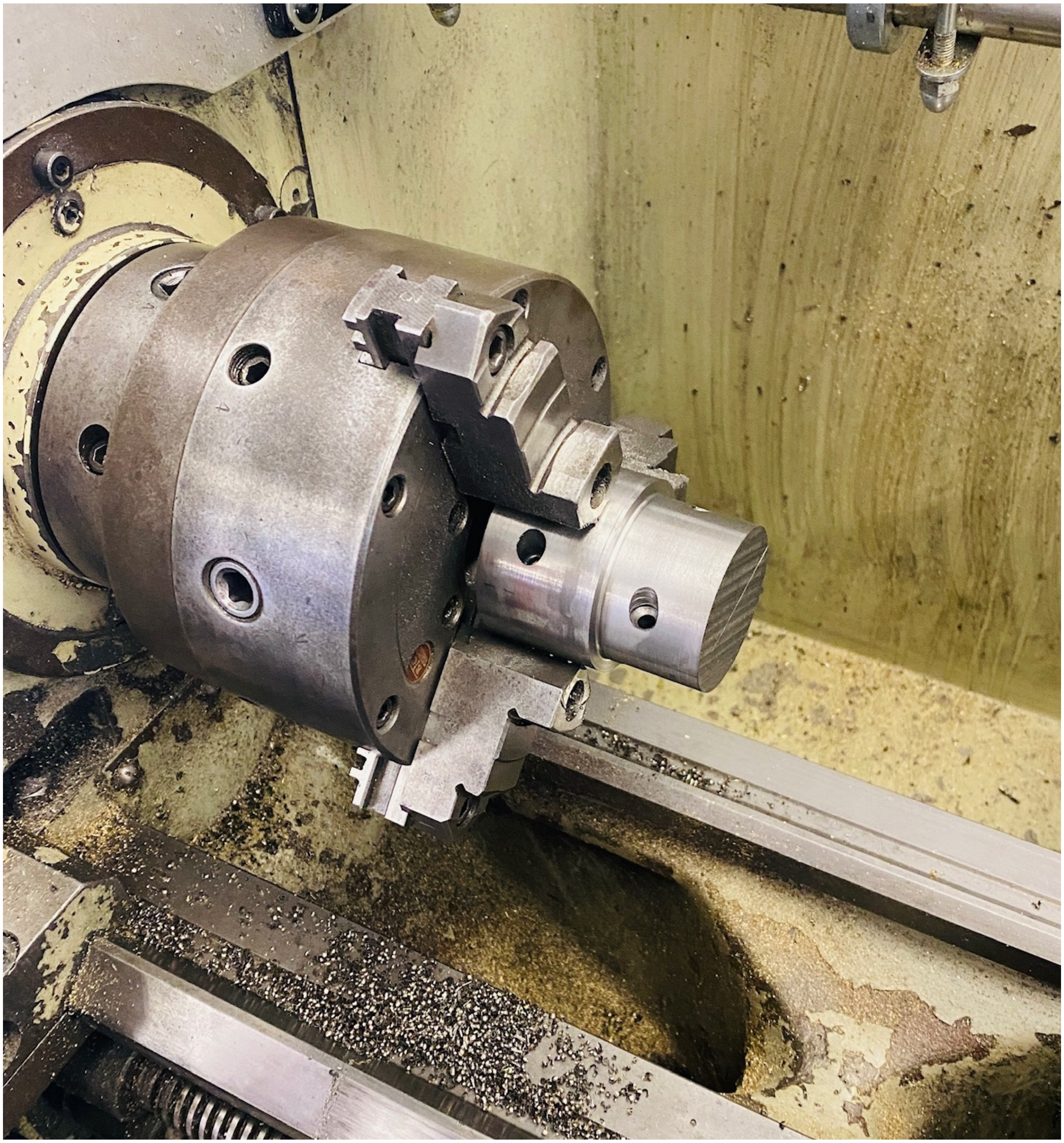
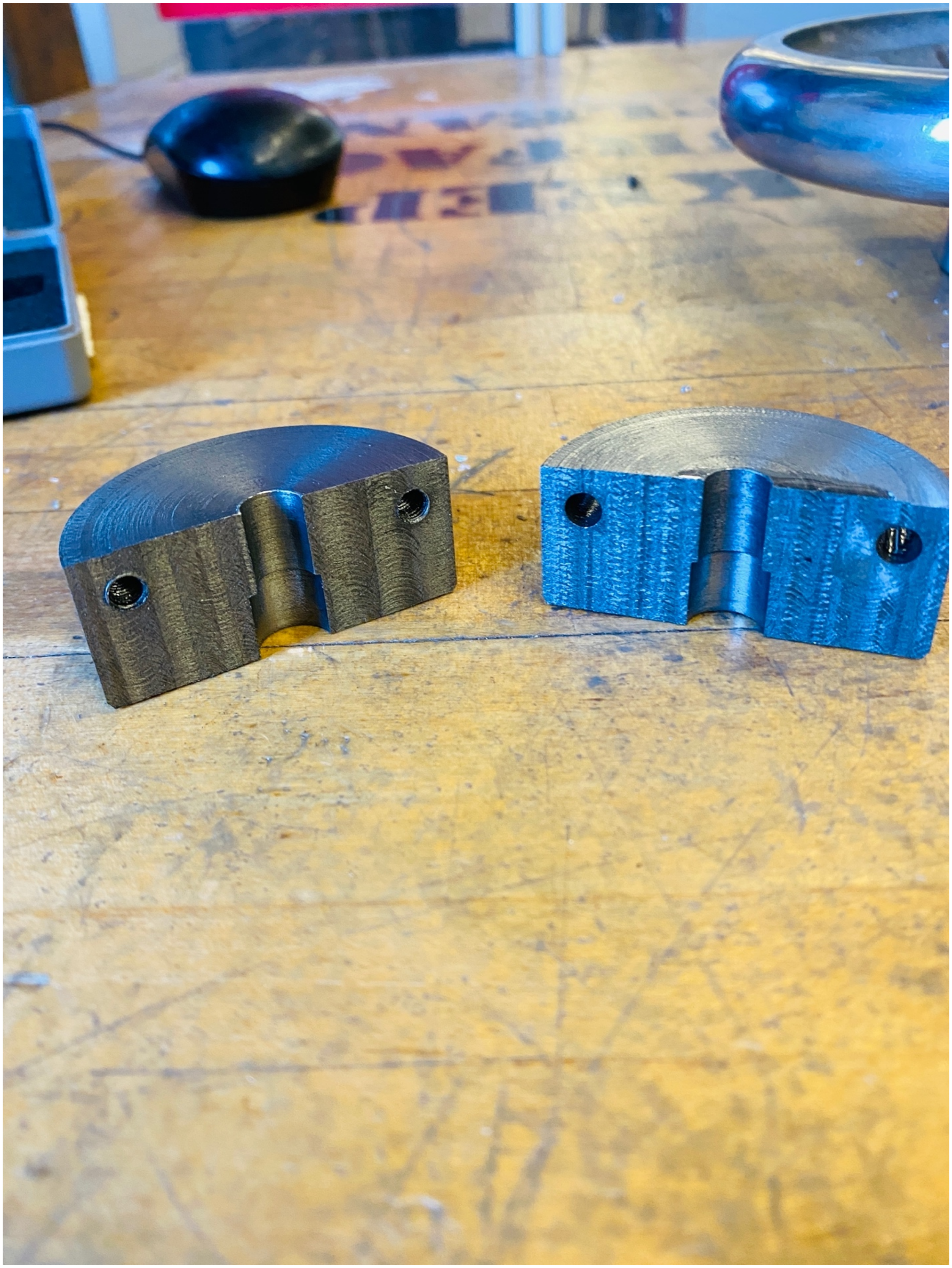
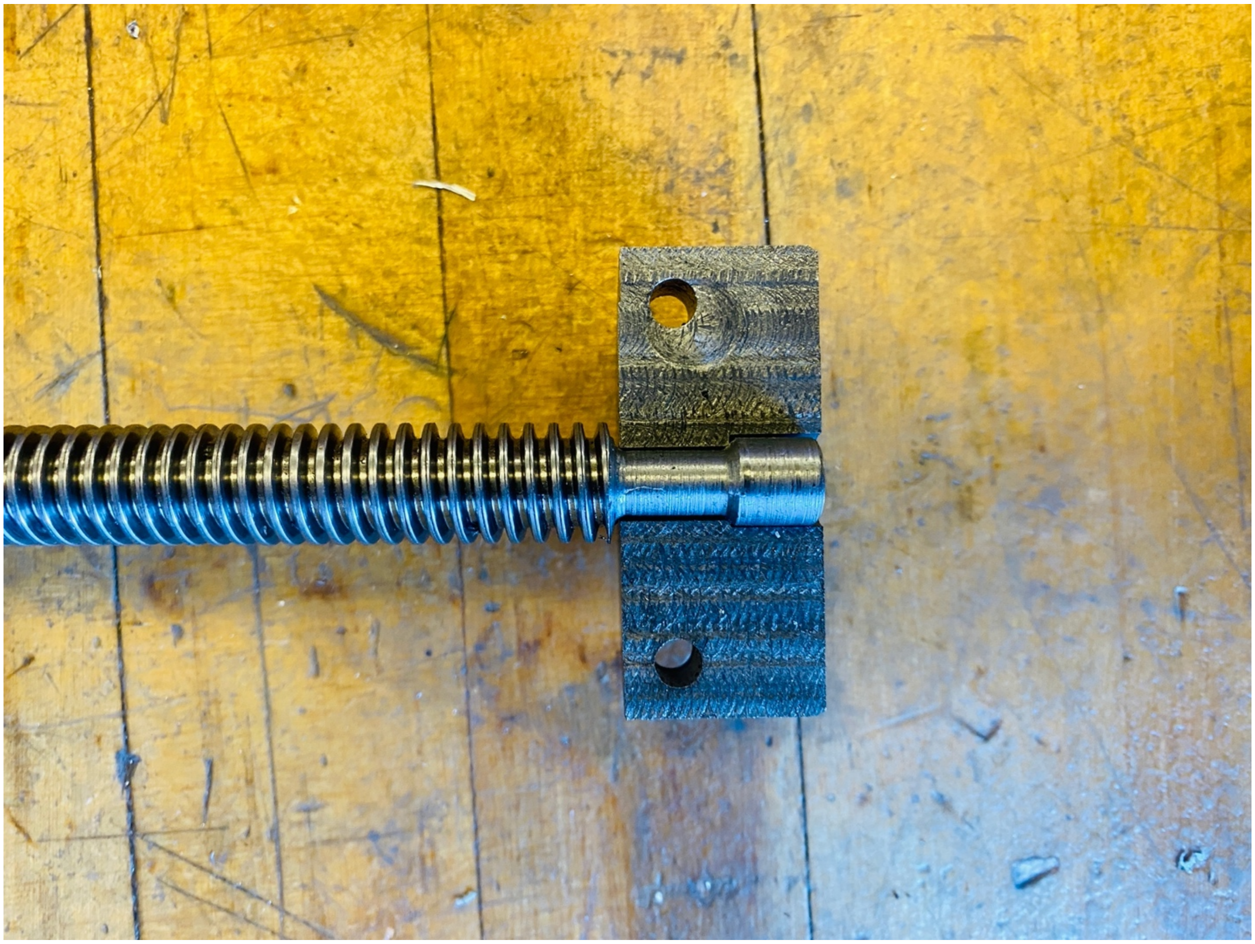
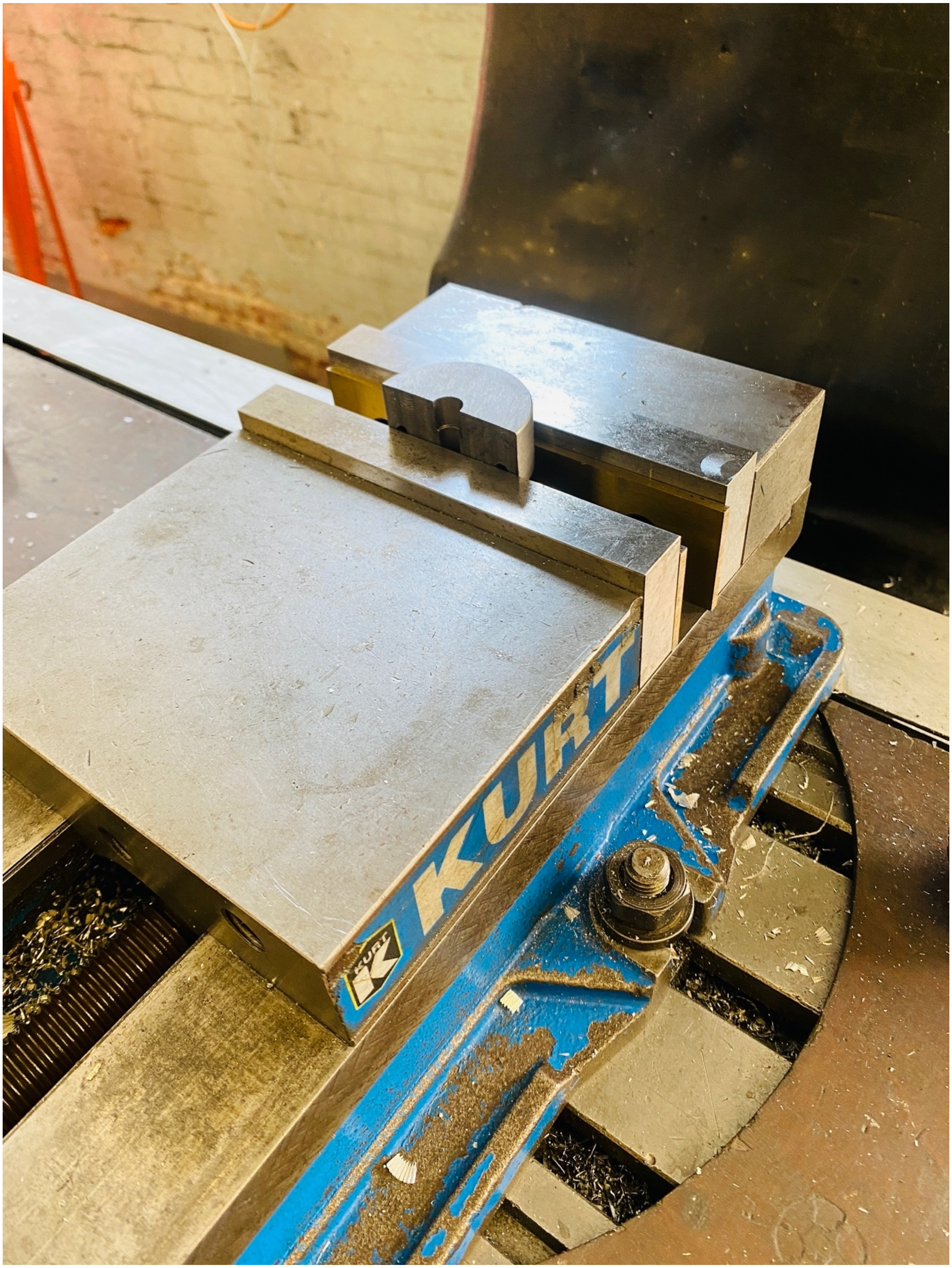

Ship To:
HIGGINS LAB - 130
100 INSTITUTE ROAD
Customer PO







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