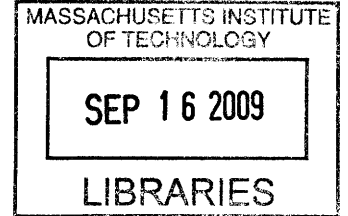


**The Design and Small-Scale Fabrication
of Precision Desktop Lathe Components**

by

Brian Philip Demers



Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

ARCHIVES

Massachusetts Institute of Technology

June 2009

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Signature of Author _____

Department of Mechanical Engineering
May 8, 2009

Certified by _____

Martin Culpepper
Associate Professor of Mechanical Engineering
Thesis Supervisor

Accepted by _____

John Lienhard V
Collins Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

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ABSTRACT

An evaluation was carried out on the design and fabrication techniques of the components provided to students in MIT's 2.72 class. These components are used by the students in the production of a fully-functional precision desktop lathe. Changes to the existing design of the provided components were made to produce higher quality parts, to lower costs of fabrication, and to increase the diversity of the manufacturing processes utilized in the class.

Much of the study was devoted to the design and production of sand cast parts. Patterns for these components were printed using stereo lithography, and then cast at a local foundry. Using a carefully designed process plan, the critical interface features of the sand cast parts were machined to their final dimensions. Specific attention was paid to the fixtures clamping these non-uniform parts to ensure accurate datums during machining.

Thesis Supervisor: Martin Culpepper

Title: Associate Professor of Mechanical Engineering

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My sincere thanks to both Professor Culpepper and to Jon Hopkins, the course TA, for their advice and support throughout the semester. Their guidance and input has been critical in getting the lathe components successfully manufactured on time, and within spec. I am also grateful to the lab instructor, Patrick McAtamney, for all the time and effort he has dedicated to the class, and to the students. His work with both me and the students has been critical in the fabrication process. Lastly, I would also like to acknowledge the Spring 2009 2.72 students, who have provided valuable feedback on my work as they have adventured through the course.

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Chapter 1: Introduction

1.1 Background

MIT's 2.72 class focuses on the area of mechanical design. To assist in the learning experience, students design, fabricate, and test miniature high-performance lathes. The task of designing and fabricating a desktop lathe in its entirety would be a huge challenge for any student. In order to do so in a semester, 2.72 focuses on key components in the machine tool. While students are expected to understand the lathe's function as a whole, certain parts, like the head and tail stocks, are provided semi-complete. They require only small modifications in finishing and mounting to integrate with the student designs. Taking the burden of design and fabrication of these parts off of the students allows them greater time to explore their own designs for critical machine components. The demand for these pre-fabricated parts, in terms of the class, is very strong. Without them, it would be incredibly difficult for the students to measure or evaluate their designs. The base components provided in 2.72 are virtually necessary to complete the course on time.

Allowing each student to build his or her own lathe requires that as many as 40 lathes worth of prepared parts be manufactured for the class during the semester. The purpose of the following work has been to comfortably allow this scale of production to occur at low cost and at a quality suitable for the needs of the class, and to provide better documentation to the students, so that they may be properly prepared to integrate their own designs with the provided components. A growing number of students are electing to take the 2.72 class each year. With this expansion, the demand for the pre-fabricated

components, and therefore, the importance of these thesis results, continues to increase. The impact of this work should be seen in both higher quality components, and the wide availability of these components, such that every 2.72 student may elect to fabricate his/her own lathe.

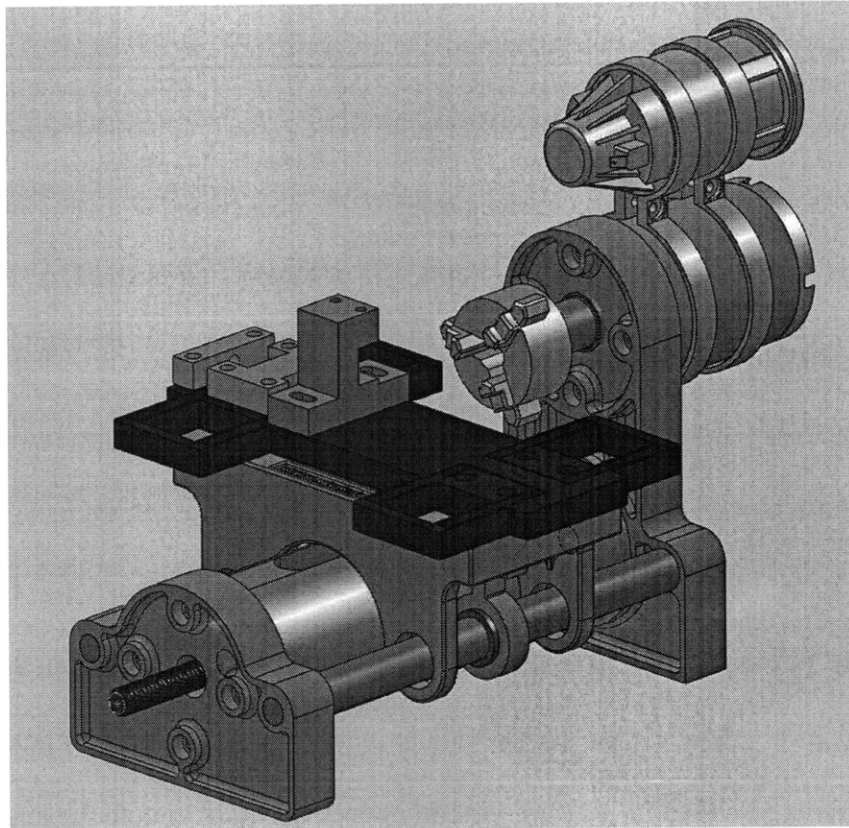


FIGURE 1.1a: THE 2.72 LATHE

The students in 2.72 are provided with dozens of components for their lathes. Some are off-the-shelf parts, and others are highly customized. The expectation of the class is that parts that are listed as *provided* will be delivered in a complete or semi-complete form so that any further customization to the specific lathe design can be done by the individual students. Of these dozens of components, the most challenging to deliver are the Head Stock, the Tail Stock, the Structure Tube and lead screw system, and the Carriage.

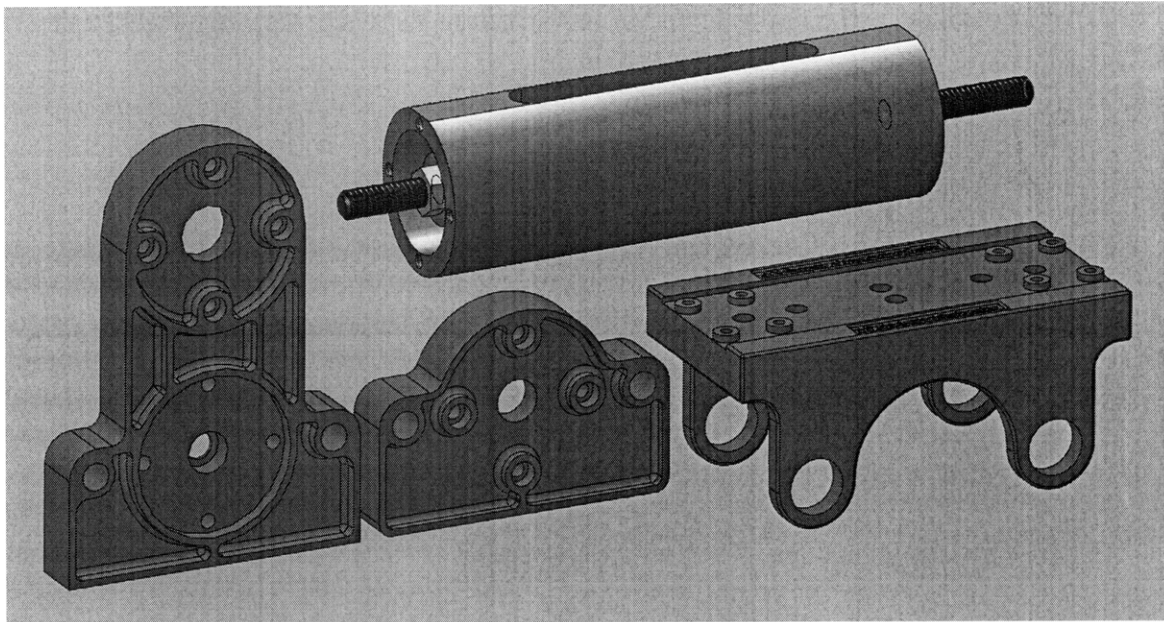


FIGURE 1.1b: FOUR MAIN COMPONENTS

These four parts comprise the major structural components of the lathe, and interface with the many custom-designed parts the students produce. Because the students are able to design their parts to interface with these components, it is critical that all mounting dimensions, clearances, and features be delivered as specified. Because of budget constraints, it is also important that these components be fabricated efficiently in terms of materials, processes, and labor.

1.2 The Components

The Head and Tail Stocks serve as the main supports that cap the ends of the lathe. The bases of these parts function as the *feet* of the lathe. The Head Stock serves to rigidly connect the Spindle Housing to the Structure Tube and the Carriage Rails, and to hold

these components in alignment with any flat surface on which the lathe rests. The Tail Stock rigidly connects the opposite end of the Structure Tube and Carriage Rails, and also holds these components in alignment.

The Structure Tube provides the main rigid support between the Head and Tail Stocks. It also contains a lead screw that drives the Z-motion of the lathe's carriage. Sub-components of the Structure Tube assembly constrain the movement of the lead screw to allow its rotation to effect translation of the Carriage.

The Carriage supports the Cross-feed Flexure and Tool-Holder, and slides on the Carriage Rails through the use of bronze bushings. It is also coupled to the lead screw within the Structure Tube by a lead screw flexure. The Carriage must rigidly pass the cutting forces of the tool through the rails and into the Head and Tail Stocks.

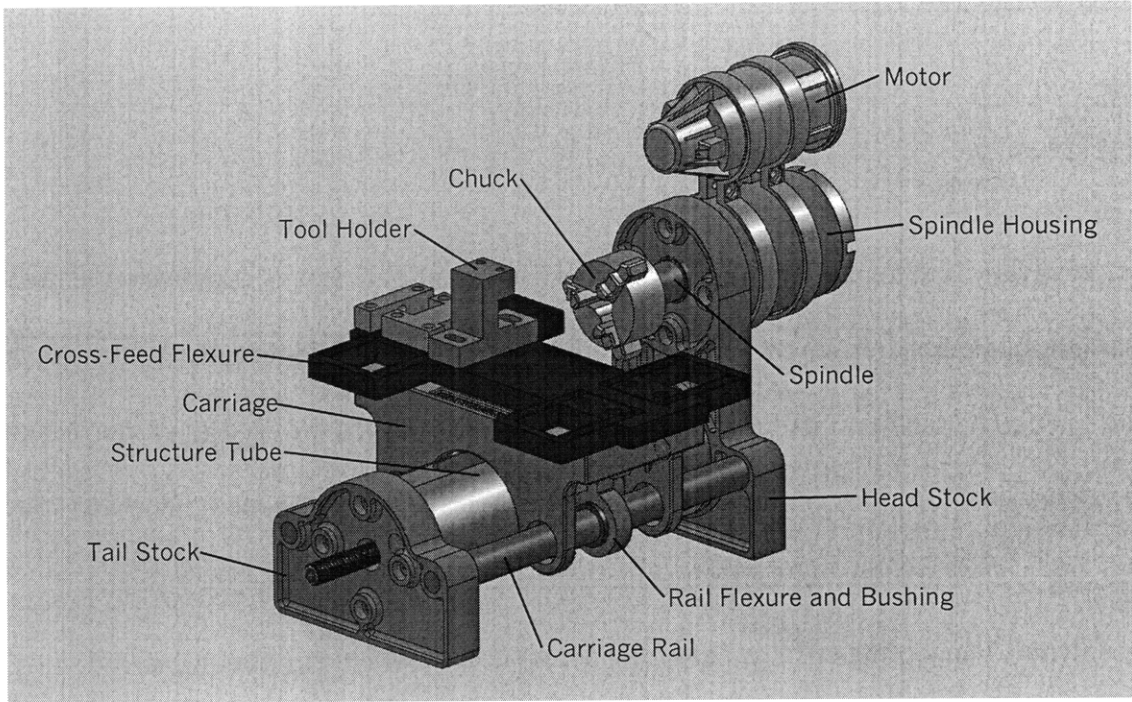


FIGURE 1.2: ANNOTATED ISOMETRIC OF LATHE

Chapter 2: The Head and Tail Stocks

2.1 Design

In previous years, a number of designs for the Head and Tail Stocks have been attempted. Some have been water-jet-cut. Some have been machined. More recently, a version was designed to be sand-cast and finished with a CNC mill. Given the success of this design, it was most efficient to optimize its fabrication and leave it dimensionally identical. Sand Casting is a particularly cost effective method of producing parts near their final geometry. The tooling costs are low, and the process is capable of producing fairly complex parts (Shigley, Mischke, & Budynas, 2006, p. 274).

In order to prepare the model to be sand-cast, an alternate *configuration* was made in the part's solid model. The *as-cast* configuration was the base of the design for the casting patterns that would later be made. This configuration featured additional wall thickness and material in the areas where machining would later create precision surfaces. The depth of both the Head and Tail Stock *as-casts* were increased to allow their fronts and backs to later be fly-cut. Their interior features, where the Spindle Housing and Structure Tube would later mount, were thickened, and diameter shrunk, so that an end mill could later pocket the area to its final dimensions. Where possible, a draft angle of two degrees was added to facilitate the mold-making process (Kalpakjian, 2006, p. 267). All corners and edges were filleted with a minimum radius of 0.075" to assist in the prevention of

cold cracking (Shigley et al. 2006, p. 274). Figure 2.1 illustrates the *as-cast* and *post-machined* configurations for one side of the Head Stock.

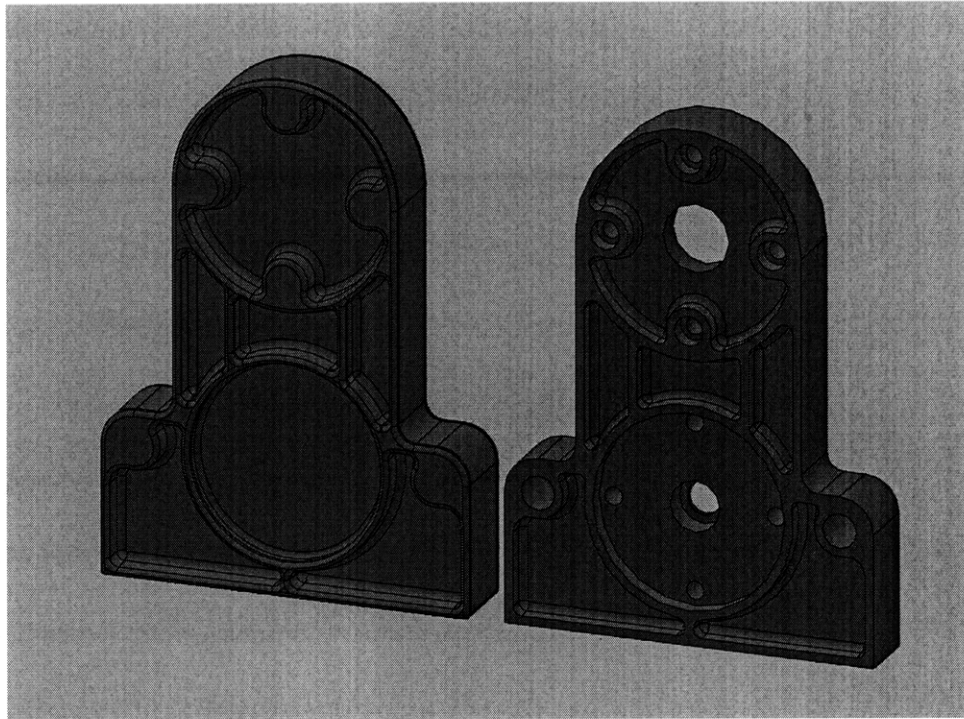


FIGURE 2.1: AS-CAST VS. POST-MACHINED HEAD STOCKS

2.2 Fabrication

The foundry selected for production preferred to work with a match-plate type pattern, where two halves of the pattern are secured to a single wooden plate (Kalpakjian, 2006, p 267). The *as-cast* configurations were converted to a pattern design by assigning a plane around which the part could be divided in two semi-equal pieces. Fortunately the plane down the center of the parts contained no features and provided a simple location to add the mold parting line. See Figure 2.2a for the four parts that comprise the Head and Tail Stock patterns.

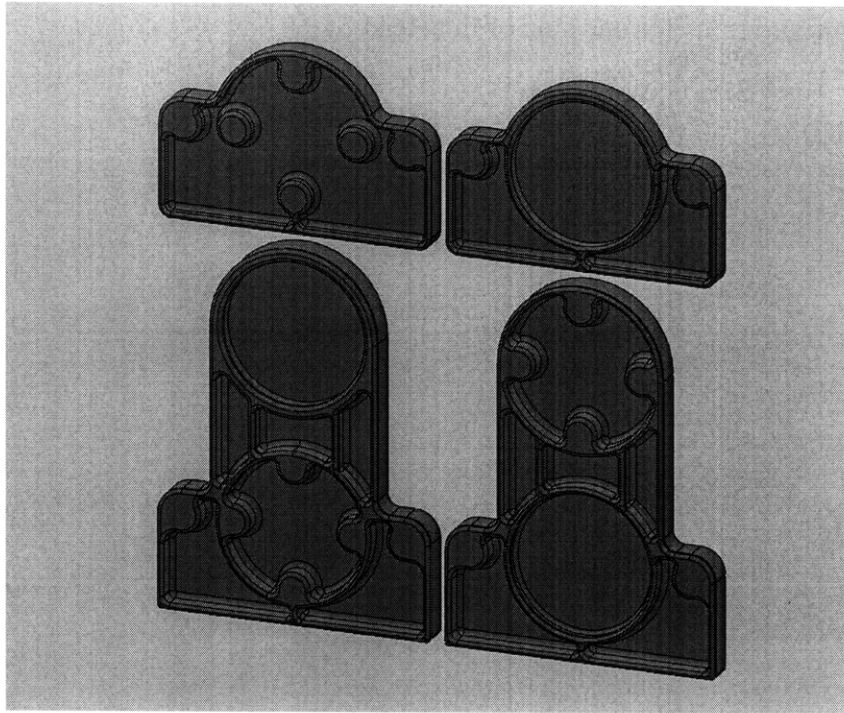


FIGURE 2.2a: THE HEAD AND TAIL STOCK PATTERNS

These patterns were then printed using a stereo-lithography printer in FullCure resin. The use of *3D Printing* for the purpose of pattern creation has become increasingly desirable (Kutz, 1986, p. 243; Kalpakjian, 2006, p. 267). This method of fabrication is simple and remarkably quick, but it has drawbacks. The materials cost of producing these parts is certainly more than if they were to be hand-crafted in the wood shop, discounting the labor involved of course. The FullCure resin has a texture and surface finish that is slightly tacky, and adheres to sand. This leaves a rougher-than-desired surface finish in the final casting. One possible remedy for the future would be to sand-blast the resin parts, and to coat them with a varnish, as has commonly been done on wood patterns (Oberg et al., 2008, p. 1368-69). This may result in a better surface finish on the cast aluminum.

At the foundry, the half-patterns were pinned together for alignment, and mounted separately on the match-plate wood. Gates, risers, runners, and sprue features were fashioned from wood and added to the patterns to allow material flow and venting (Kalpakjian, 2006, p 265). Once *green sand* had been packed around the half-patterns, they were removed, and the two boxes of sand (the cope and drag) were joined and locked together. Aluminum was poured through the Sprue, and filled the voids within the sand pattern. The Head and Tail Stocks were cast side-by-side in the same cope/drag set for time efficiency.

The cast parts were first band-sawed from the gates and risers, and then ground and sandblasted to remove imperfections. These processes, although necessary, compromise the integrity of the outer edges of the part. However, these abrasive methods are less likely to damage to the internal features most critical to the parts (Oberger, & McCauley, 2008, p 1367). Because of these cleanup operations, the corners were oftentimes not perpendicular, and edges not parallel. Given the primary purpose of the Head and Tail Stocks, it was of utmost importance that their critical mounting dimensions be accurate. This would be taken care of by the next process steps. The inherent benefit of a machined casting is that the machine tool can form all critical features. Doing so allows tight control over their relative locations, tolerating minor misalignments of the bulk cast material (Kutz, 1986, p. 269). The features of the Head and Tail Stock, however, required machining on both the front and back of the parts. Without access to a fourth-

axis mill, it was necessary to rotate and re-clamp the parts to complete the machining process. Doing so meant that a robust set of alignment features needed to be identified.

On the parts as they were cast, the edges most accurate to the design were the front and back faces, which had undergone little to no grinding at the foundry. The base, or *foot* of the parts was the second strongest alignment feature. Using these surfaces, the Head and Tail Stocks were mounted upright in a vice on a Bridgeport mill. A flat was fly cut in each at a specified height off of the base of the vice. This flat at the top of the parts would later provide a mounting surface. Due to the variability in the parts, the depth of cut in this operation was different on each part. Some required two depth cuts to ensure a proper surface finish on the finish cut. The parts were then inverted, and balanced on the new flat. The front and back faces were again clamped for alignment in the mill's vice. The *foot* of both parts was fly cut at a specified height. This time, due to the prior operation, the depth of cut was consistent between parts, yielding parts that now all had the same height.

The height of the machined features relative to the machined base was the most critical issue, so that the lathe, when assembled, would sit square on a flat surface. The left-right alignment of the features was less critical, so long as it was consistent front-to-back on the parts. In consideration of the time required, no machined flats were made on the left and right edges of the parts. Rather, a fixture was designed for the mill that would aid in alignment. Custom *soft jaws* were machined with a step surface to accommodate the Head and Tail Stocks in a laid-down position. The y-axis was zeroed at the top, non-

moving jaw. The *foot* of the parts was placed against this jaw. The z-axis was zeroed at the base of the vice jaw's step. This allowed the parts to be fly-cut to a known, repeatable thickness. The x-axis alignment was more difficult, as it had to accommodate the rotation of the parts. The custom jaws featured two alignment pins to fix the x-axis of the part. See Figure 2.2b. The part was first loaded in the left configuration. On the *foot end* of the part, an alignment pin contacted the edge, providing an x-axis datum. After the part had been fly cut, and otherwise machined, the part was rotated, as in Figure 2.2b, to its opposite side. A second alignment pin contacted the part in the same datum location. This defined a new coordinate system in which to machine the opposite side of the part. Since the edges on which the datum was set were not always perpendicular to the base of the vice, it was critical that the pin contact the same exact point, and not just any point, on the edge of the part. This was ensured by placing the first locating pin at a z-height such that when the part was machined and rotated, the second pin would contact the same datum point as the first pin. This too is illustrated in Figure 2.2b. This operation was specifically enabled by the choice to set the z-axis datum on the bottom of the jaw's step, rather than on the top of the part.

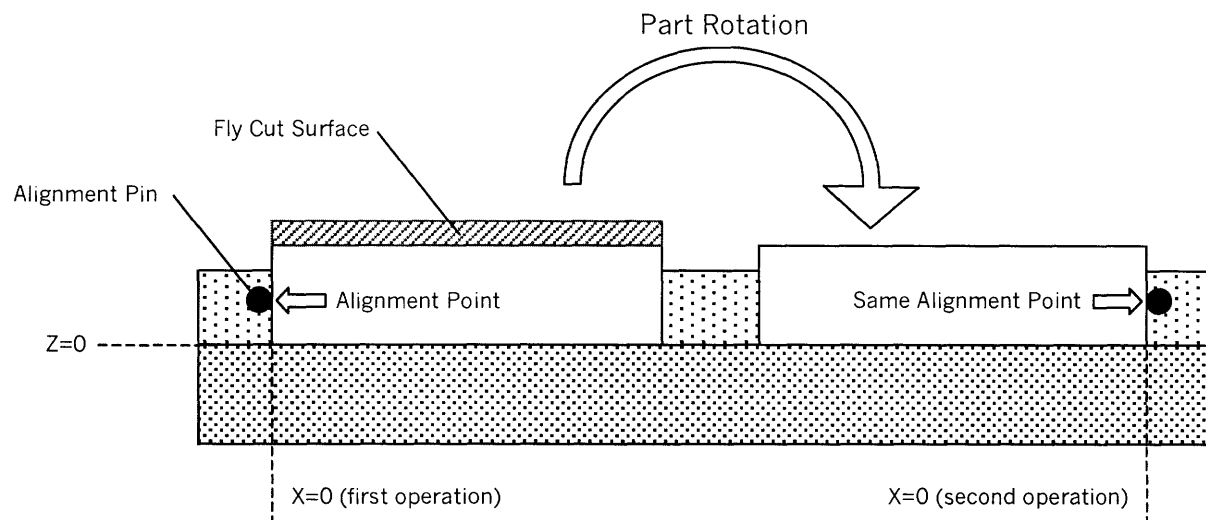


FIGURE 2.2b: MILL VICE SIDE VIEW

The pockets that receive the Structure Tube and the Spindle Housing also contain clearance holes for mounting screws and larger thru-holes for the lead screw and spindle shaft. To ensure these features were concentric, their respective groups were all machined and drilled from a single side. The counter-bores for the clearance holes were necessarily machined from the opposite side. The x-axis pin system described above was effective at ensuring the counter-bores aligned with their thru-holes. By setting the z-axis on the base of the vice jaw step, the final fly-cut maneuver ensured that all Head and Tail Stocks were machined to one inch thick, regardless of their starting value from the foundry.

Chapter 3: The Structure Tube Assembly

3.1 Design

The assembly connecting the Head and Tail Stocks and providing lead screw operation in previous design iterations was costly, and required many complex parts. In this design, the Structure Tube was simplified to one tube, and two small plates, in addition to lead screw hardware. This cut costs in materials, and greatly reduced manufacturing time.

On the exterior of the tube, a flat is machined to aid in alignment of the end features.

Within the flat, a pocket is machined to give clearance for the lead screw flexure to pass.

A step on the interior of each end of the structure tube provides a flat for an annular plate to rest upon. See Figure 3.1a for details. The plate supports a bushing and bearing system that properly constrains the lead screw. Threaded holes on each end, aligned to the exterior flat, bolt the Structure Tube to the Head and Tail Stocks.

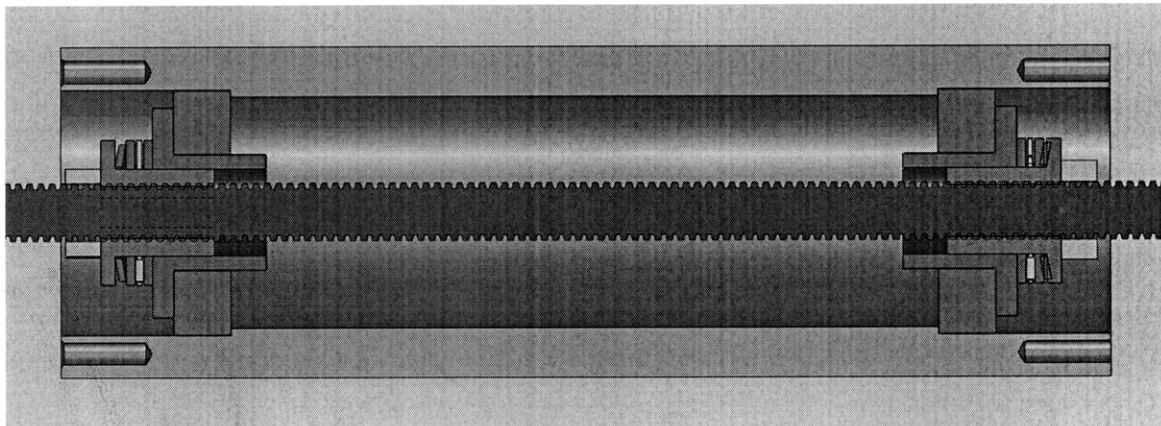


FIGURE 3.1a: LEAD SCREW ASSEMBLY CROSS-SECTION

The lead screw, a 1/2-20 threaded steel rod, is held by two threaded Flange Nuts. These Flange Nuts are radially constrained by Bronze Bushings in the Annular Plates. Because of the low speeds and low loads necessary on this lead screw, the bronze, self-lubricated bushing is appropriate for the constraint required (Shigley, & Mischke, 1986, p 19.5). When tightened on the threaded rod, the Flange Nuts apply preload force through a Belleville washer, acting on a set of thrust-bearings. These thrust bearings translate the preload force to the bushing, and through the annular plates into the structure tube. A preload nut on each end provides locking force against the Flange Nuts. An annotated diagram of the preload and bushing mechanism is shown in Figure 3.1b.

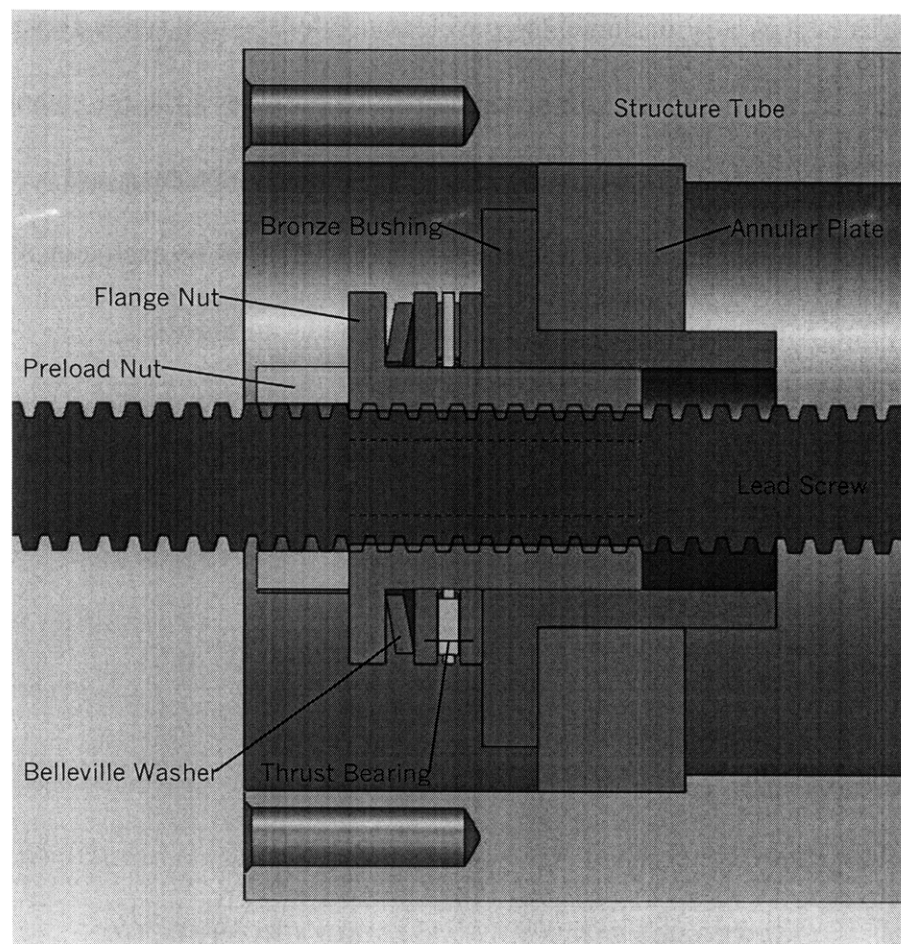


FIGURE 3.1b: ANNOTATED PRELOAD MECHANISM CROSS-SECTION

This simplified design requires only the custom manufacture of the Flange Nuts, the Annular Plates, and the Structure Tube.

3.2 Fabrication

The Structure Tube itself was contracted out to a local machine shop for fabrication. All machining was completed on CNC equipment. The Flange Nuts were also contracted out, and were turned on a CNC lathe.

The Annular Plates were water-jet cut from aluminum sheet in the MIT Machine Shop in a batch operation.

All other parts were specified as off-the-shelf parts, and were purchased from various suppliers.

Chapter 4: The Carriage

4.1 Design

The Carriage featured a clean-slate redesign in this model. Previous versions of the Carriage were made from water-jet-cut aluminum and a polymer block. Although the design was very easy to make, the cost of the abrasive and maintenance in the water-jet cutting operation as well as the material costs for the polymer were not justified by the performance of the Carriage. The use of the polymer, in particular, left a soft base in which to bolt the cross-feed-flexure. These bolts often stripped the threads in the polymer during use.

Given the plethora of lathes that have been made in prior years, it made sense to keep all the critical mounting dimensions and positions the same as previous models. Therefore, parts like flexures could be interchangeable between models for testing or experimentation. The mounting locations included: supporting two bushings on the near-side rail, bolting to the lead screw flexure, bolting to the rail flexure, bolting to the cross-feed flexure. The rail flexure served to prevent over-constraint in the carriage mount; only one side of the carriage needed to rigidly mount through bushings to the rail. However, in order to simplify the manufacturing process, and to ensure quality parts, the Carriage was designed to be symmetrical, and reversible. In doing so, any shrinkage or errors from the casting process would be symmetric about the middle of the part. Like the Head and Tail Stocks, the Carriage was designed to be sand-cast and then finish-

machined. Sand casting was chosen for its low cost, and its ability to make complex parts in an inexpensive manner (Shigley et al., 2006, p. 274). Sand casting is especially economical for parts of small to medium runs, as the tooling costs are very low (Kalpakjian, 2006, p. 264). By casting the near-net shape, only a small amount of material needed to be removed by finish machining.

The final Carriage featured a top plate area, with four separate *wings* extending downward. See Figure 4.1a for an isometric view of the finished part. On the top plate, there were eight raised bosses with threaded holes on which to mount the cross-feed-flexure. These bosses kept the flexure seated at the proper height, and prevented it from rubbing on the rest of the carriage's top surface. Each boss on the top extended down from the bottom of the plate as well, providing additional length for the threads to engage and increasing the robustness of the part. See Figures 4.1b and 4.1c for the top and bottom views of the finished Carriage. Clearance was machined in the center of the top for a polymer bed, which optionally provided a surface in contact with the moving flexure, should the user wish to insert damping grease. Thru-holes in the left, right, and center of the top plate of the Carriage were drilled to mount to the lead screw flexure, and the rail flexure underneath. Like the threaded bosses, each set of thru holes was accompanied by a boss on the underside, which provided stiffness, and located the mounting point at the appropriate dimension. The four *wings* extended down from the top plate to the area of the rails. The holes in these wings were drilled on one side to accept a bronze bushing. On the other side, the holes were drilled for rail clearance. Only one pair of wings would ever be used at one time to prevent over-constraint. The

underside of the Carriage featured five support ribs. These ribs connected the bosses to the main top plate, and to the wings. Two of the ribs extend down the side of the wings, providing support in what would later be the lathe's z-axis. The top plate itself was designed to be thin, so that the ribs could provide additional support where needed, and to save material where possible.

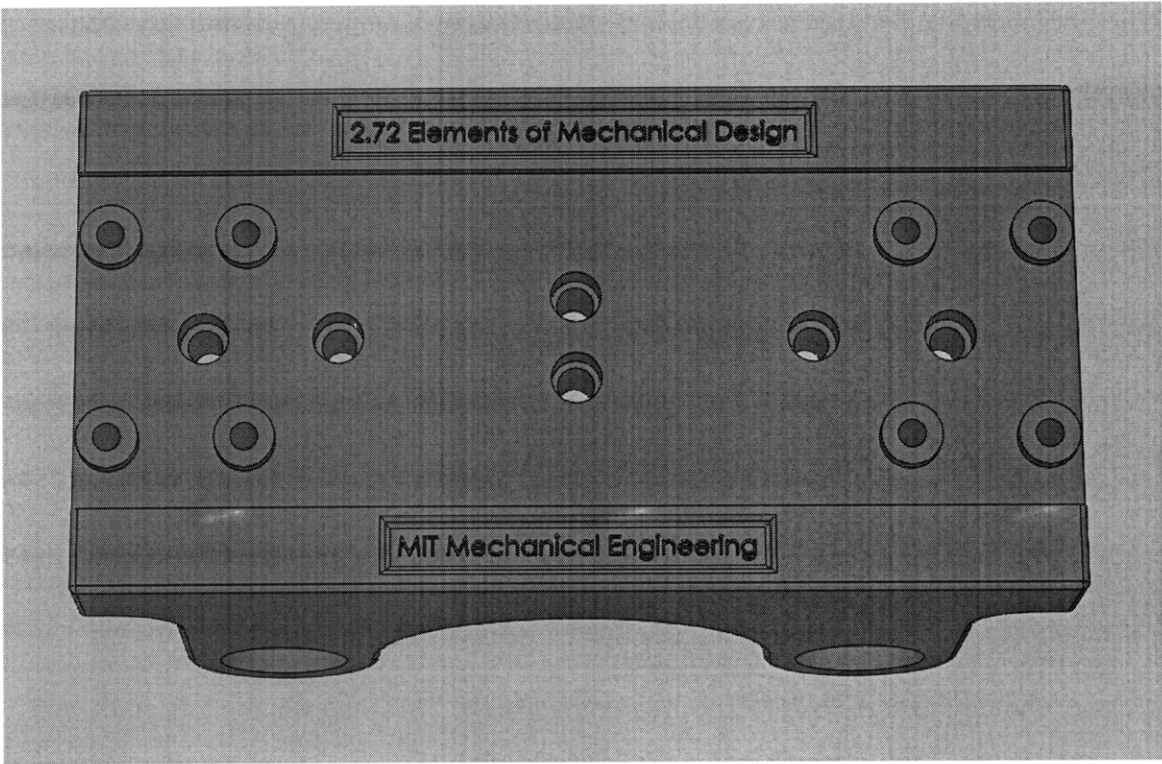


FIGURE 4.1a: CARRIAGE FROM TOP

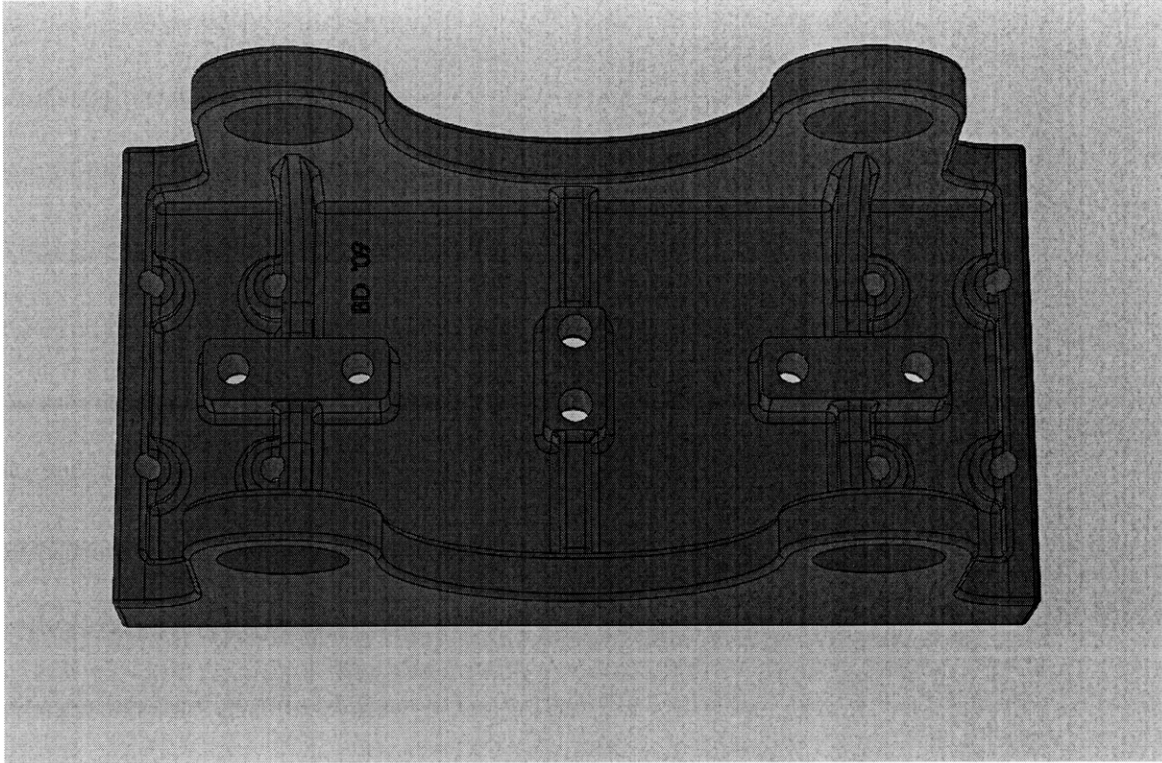


FIGURE 4.1b: CARRIAGE FROM BOTTOM

In preparation for casting, the solid model, like that of the Head and Tail Stocks, was arranged in a second configuration. In this configuration, all of the holes were removed, although the bosses remained. The pocket for the polymer bed was also eliminated. The eight bosses on the top surface were extended further, so they could later be machined to height. Figure 4.1c illustrates the *as-cast* configuration of the Carriage.

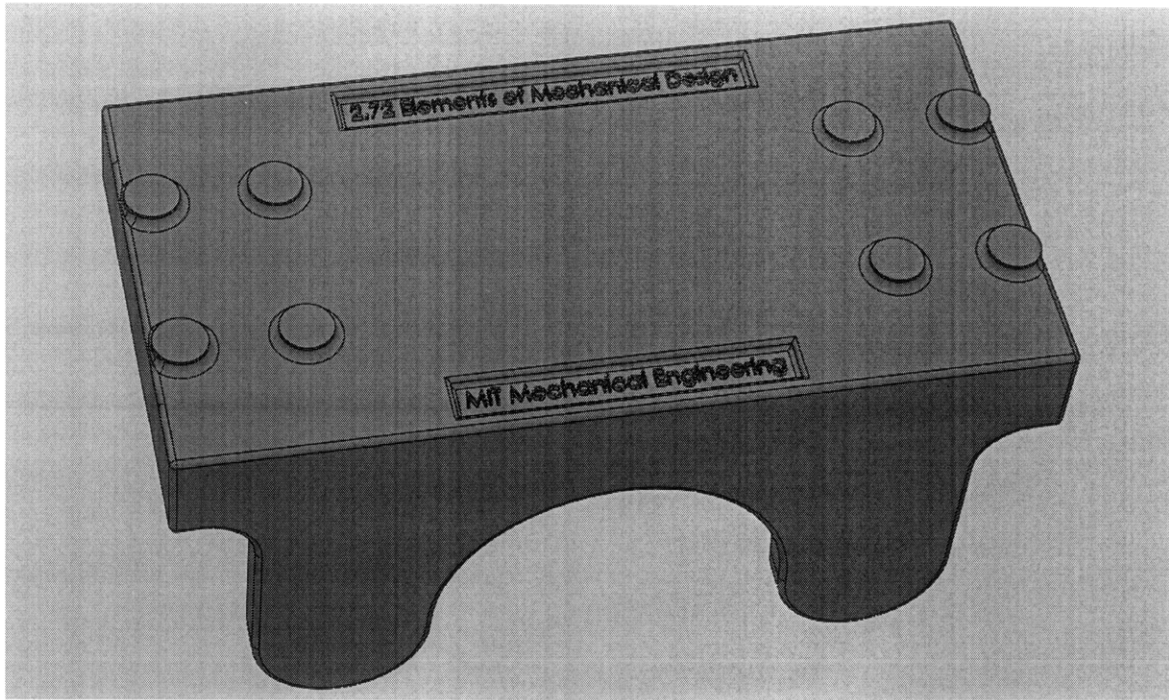


FIGURE 4.1c: AS-CAST CARRIAGE

4.2 Fabrication

As was done for the Head and Tail Stocks, the *as-cast* configuration was divided in half, and stereo-lithography printed into patterns. Once again, the parting line conveniently fell in the middle of the top plate, where no critical features were found. The Carriages were cast two-per cope/drag set to increase efficiency and decrease cost. The issue of utilizing a dual cavity mold was the concern that the parts may not be dimensionally similar. No dimensional mismatch between the two patterns was found in this case. As with the Head and Tail Stocks, gates, runners, risers, and a sprue were added with wooden blocks.

To complete the Carriages, they needed to be finish-machined. Unlike the Head and Tail Stocks, most of the features could be machined from one clamped position. This somewhat simplified the fixturing process. The carriages were held in their standard orientation in a set of tall jaws. The bottom of the wings served as the z-axis zero. A stop on the vice engaged with the left end of the top plate to serve as the x-axis zero. A CNC routine faced off the eight bosses, drilled them, and tapped them. It also pocketed the polymer bed clearance, drilled the six clearance holes, and pocketed their counter-bores. An engraving tool was used for a custom engraving during this routine. The order of machining operations was optimized to minimize the number of tool changes necessary.

Because all of the interface surfaces were machined, the accuracy of the z-axis zero was not particularly important in this operation, except that if it was too low, the bosses would be fly-cut below the surface of the casting. If this were the case, the flexure would not sit proud of the casting, and might rub in certain locations. This issue in future attempts could be corrected in two ways: Including a fly-cut pass that sinks the top surface outside of the polymer bed pocket. This would guarantee clearance. Another possibility would be to invert the carriages before machining, and to machine flats in the bottom of the wings, in a way similar to what is done with the Head and Tail Stocks. The bosses do appear to be the best datum surface on the cast parts. Adding an additional fly cut pass on the top side would be most efficient labor-wise.

The next feature to be machined was the flats on the underside to which the flexures mounted. These flats were designed to be exactly one inch below the top of the bosses. Once the CNC process was complete, a user could invert the part in a Bridgeport mill. After setting a z-axis zero on the base of the vice, the user could fly-cut at one inch to produce these flats.

Lastly, the bushing and clearance holes for the rails needed to be drilled. The location of these holes relative to the other machined surfaces was critical to the smooth operation of the lathe. When the Carriage was oriented for drilling, none of the machined features were easily accessible to set an x-axis zero from. Therefore, a locating jig was necessary. The jig consisted of a ½” thick plate with two pins. These pins engaged with the counterbores in the top surface. One end of the jig was machined at a precise distance from the pins. This provided an accessible surface to slide against a stop in the Bridgeport mill. After one side of holes was drilled, the Carriage could be removed and flipped. The use of the jig ensured that the holes on both sides were concentric, and centered around the machined features on the top surface. Figures 4.2a and 4.2b illustrate the directions provided to students to assist in using the jig.

DRAWING 1

Insert the jig into the carriage. Note that the left side is the machined surface.
Set your Y-zero off of the inside of the top vice jaw. Clamp the part (this is the top view of the Bridgeport).
Set your X-zero off of the MACHINED surface. Your origin should be the top left corner of the jig.
Drill the bushing bores in the appropriate locations (see dimensions below). Use a drill size corresponding to your bushing selection. Go slow, 100-150 rpm max!!!
A 1" drill is sitting at the machine for your use. Center Drill first!

Remove the carriage, reverse the jig, and reinsert (with machined surface still left) against the stop to drill the other side's holes.

Proceed to DRAWING 2

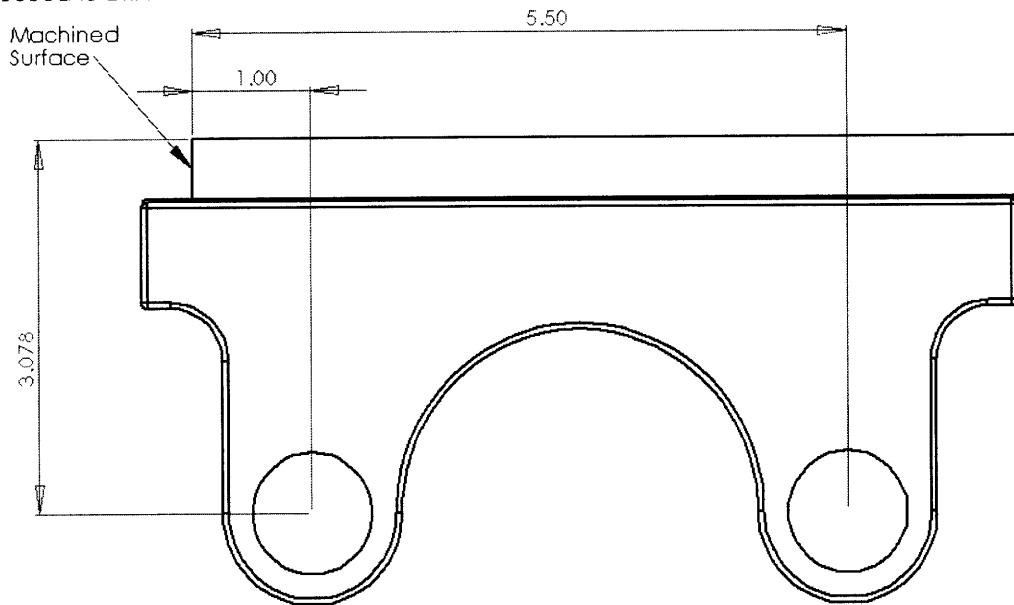


FIGURE 4.2a: JIG INSTRUCTIONS PAGE 1

DRAWING 2

Remove the jig from the carriage. Load the 1" endmill into the Bridgeport. Set a Z-zero on the bottom of the vice. (do not do while tool is spinning) Raise the tool. Clamp your part (without the jig) so that it rests on the bosses. (this is the Bridgeport top view). Drop your endmill to 1" above the vice bottom, and fly-cut the three mounting points. (shaded here)

File as necessary.

YOU ARE DONE !!!

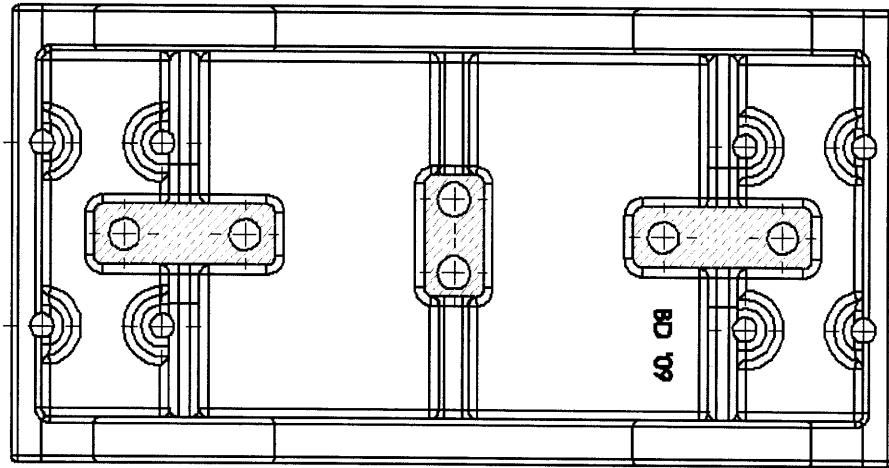


FIGURE 4.2b: JIG INSTRUCTIONS PAGE 2

Chapter 5: Conclusions

The students in the Spring 2009 2.72 class have been able to successfully assemble their lathes with the new provided components. No performance or fit issues have been reported. The number of cast parts used, which approached 120 for this course alone, did prove to be a large burden on the course staff and instructors, however. Although the machining process was automated, the loading and unloading of the parts was not. The time interval between parts, ranging from 10 to 20 minutes, depending on the part, was long enough to necessitate that Pat, the lab instructor, attend to other students. It proved difficult to keep the parts consistently flowing through the CNC process. Although cost would certainly be an issue, the class instructors may wish to have the CNC work done by an outside shop, as was done for other parts like the Structure Tube. Another option for consideration would be the hiring of an undergraduate to complete all machining operations during the Spring Break week. If the parts were consistently loaded into the mill, the entire batch could likely be completed in 5 days.

In addition to the delivery of the parts for this semester, an updated series of solid models and drawings has also been provided to the class and instructors. Along with these models are the CAM programming required to perform the cleanup operations on the cast parts. These files, along with the actual patterns used for the sand casting process, will minimize the up-front labor necessary to fulfill the fabrication of these parts for the Spring 2010 class.

Lastly, the students and instructors have been provided with photo and video documentation of much of the fabrication processes, including sand casting and CNC machining of the Head Stocks, Tail Stocks, and the Carriages. This documentation should help the students in future classes better understand the origin of the components and materials that they are working with.

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