CAPSTONE DESIGN COURSE

MIM 1501-1502

Technical Design Report

Metallographic Specimen Polishing Attachment
Project # W98/S98-4

Final Report

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Professor Messac:

The manual grinding and polishing of a metallographic specimen is a process that requires extensive practice and skill. If an operator does not possess this skill, producing consistent acceptable specimens is difficult. The major challenge in this process is keeping the axis of the specimen perpendicular to the platen of the polishing machine at all times. If the specimen is not kept consistently flat to the wheel, the magnified specimen will appear out of focus. Our goal as a team is to design and produce a device that eliminates this source of error.

The following report, submitted for your approval, outlines the progress the design team has made in solving this problem. This progress includes a detailed final design, and the construction of a prototype based on this design. This report also details the success achieved during our testing and evaluation, the progress of our patent application, and recommendations for improvements which would further improve the performance of the design.

Most existing devices are not only fully automated, but are very expensive and vendor-specific. Our design is an inexpensive alternative that allows the operator interface necessary to gauge process variables such as specimen travel speed, applied force, and process time.

We appreciate the time taken to review this report and look forward to any comments or questions you may have.

Sincerely,

J. S. Conover  
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Cc: Prof. Blucher
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Abstract

The manual preparation of metallographic specimens is a process widely used in industry and research to examine the microstructure of metal samples. Unfortunately, this procedure requires skill and practice to produce specimens that clearly display all of the microstructure. This design project developed a device that will remove as much error as possible from the grinding and polishing steps of metallographic preparation. A product study and a patent search indicated that a low-cost grinding and polishing attachment, capable of adapting to multiple polishing machines, would appeal to many laboratories that cannot afford an automatic polishing device. After developing and evaluating several concepts, we chose to concentrate on developing a design that mounts on the housing of the polishing wheel and achieves its accuracy through an adjustable spherical bearing. Some of the advantages to this design include its simplicity, its flexibility for installation in a convenient and comfortable manner, and its low cost. The prototype was built for $350, and the projected production cost is lower. 100% of the specimens polished using the device proved to be usable by our definition; only 17% of the manually polished specimens were usable. We anticipate that using this device will allow any operator to significantly improve the quality of polished specimens.
Acknowledgements

The success of this project is due to the assistance of several members of the Northeastern University community. We would like to express our sincerest thanks to Professor Joseph Blucher for advising our design team. His insight, experience, patience, and support have been essential to the progress and success of our project. We would also like to thank Professor Achille Messac for providing an environment that inspired and motivated our team, and Professor Deanne Harper for providing valuable feedback and writing guidance. In addition, the team is grateful for the assistance of Jonathan Doughty and Matt Ulinski, who provided time, services, and resources for prototype production. We would also like to thank Janelle Helser, Alin Moss, and Professor Blucher who helped evaluate our prototype and provide constructive feedback on our design. The team would like to thank Richard McNeil and the members of the university patent committee for considering the novelty of our design. Finally, we would like to thank Jim Hinds for the color photography used in our presentation and reports.

In addition to Northeastern faculty and staff members, we would like to thank those in industry who provided information, time, opinions, services, and prototype material. The list of professionals who provided direct assistance includes: Philip Magee and Ray Metcalf of Smith & Nephew Endoscopy; John Pope, Eric Connolly, and Fredrick Medanich of Design Continuum; Dennis Rand and Al Ryalls of Accurate Metal Finishing; Jim Doughty of Motion Industries; Southco Inc.; David Winkel of SKF; and Fred Koehler of SolidWorks.
1. Introduction

The manual preparation of metallographic specimens is a process widely used in research and industry to examine the microstructure of metal samples. This procedure uses largely standardized techniques and equipment, but requires a large degree of practice and skill by the operator. Human error makes it difficult to prepare high quality specimens consistently. This design project will develop a device that will remove as much error from the grinding and polishing steps of metallographic preparation as possible.

1.1 Metallographic Grinding Process

During the grinding process, the surface of the specimen to be examined is made flat by rubbing the face with abrasive grit. The current methodology for grinding and polishing involves the use of a polishing wheel, which spins an abrasive paper or cloth disc against which the operator holds the specimen. The paper is fastened to a precision-ground eight-inch diameter steel platen rotating in a fixed housing. A stream of water is directed onto the paper disc during grinding. This water reduces frictional heating of the specimen, which can degrade the sample’s surface finish. The water stream also flushes particles and chips from this process off of and away from the grinding surface.

Figure 1.1 Polishing Method
Sample preparation consists of a series of grinding operations employing successively diminishing grit sizes. The process begins with coarse abrasive paper, typically 240 grit. (Grit numbers increase with decreasing grit particle size.) The operator holds the specimen with minimal force against the spinning abrasive disk. The specimen must be held flat to the platen during this grinding step; this is crucial to obtaining an optically flat surface. To aid in grinding, the orientation of the specimen with respect to the wheel should not change. When the only scratches present on the sample are those created by the 240 grit paper, the first grinding step is complete.

The next step uses the next finer grit of abrasive, usually 320 grit. Between any grinding steps, the operator must wash the specimen thoroughly to avoid depositing coarse abrasive particles on the next, finer grit paper. The operator again holds the specimen against the spinning disk, rotated a quarter turn from the previous orientation. In this position, the new scratch marks will be easily differentiated from the previous scratches. This operation is complete when all of the previous, coarse scratch marks have been replaced with new, finer marks. As grits and corresponding scratch marks decrease in size, the use of a microscope for surface evaluation becomes necessary.

This process of washing, changing papers, and grinding is repeated for increasingly finer grits. After finishing with the finest grit paper, the specimen can be polished.

1.2 Metallographic Polishing Process

Polishing is an abrasion step using diamond particles suspended in a paste. A polishing cloth spread with this paste provides the precise abrasion necessary to obtain an optically flat surface. The operator holds the specimen against this cloth, which is also mounted to a spinning disk. As with grinding, a polishing step is complete when the scratches from the previous step are removed. The specimen must be kept perfectly flat to the platen during all polishing steps.

The specimen can be polished using increasingly finer diamond pastes until no scratches can be seen at the magnification of interest. Washing the specimen between these steps is crucial to obtaining an optically flat surface. During polishing, the use of paste makes running water on the disk unnecessary.
1.3 Problems with Specimen Preparation

The challenge in specimen preparation is keeping the specimen completely flat to the platen. This can be achieved by maintaining the axis of the specimen perfectly perpendicular to the grinding surface. After the operator lifts the specimen to inspect the grinding surface, he or she might easily replace it to the wheel in a tilted position. This misorientation will cause the specimen to become facetted, destroying the flatness of the surface.

Even though these facets appear superficial, they become a significant issue when examining the specimen under high magnifications. At these magnifications, the goal is to always have a sharp, focused picture as shown in Figure 1.2. A faceted specimen will not be in focus along the entire field of view, appearing sharp in some places and blurred in others, illustrated in Figure 1.3. A blurred picture is often inadequate and requires the operator to prepare the specimen again.

![Flat Specimen vs. Faceted Specimen](image)

**Figure 1.2 and 1.3 Flat Specimen vs. Faceted Specimen**

1.4 Depth of Focus

Determining the required precision for the grinding operation requires an understanding of the depth of focus. The depth of focus, or vertical resolution, is defined as the range above and below which the image appears in sharp focus [1]. Thus, any point on the surface of the specimen cannot be above or below any other point by more than this value.
The depth of focus is calculated using equation 1

$$h = \frac{\lambda \sqrt{n^2 - NA^2}}{NA^2}$$ (1)

where \(\lambda\) is the wavelength of light (0.55 microns), \(n\) is the refractive index of the object (around 1.5), and \(NA\) is the numerical aperture of the microscope. The numerical aperture is the practical limit of magnification, and is determined by the objective lens of the microscope. Under a magnification of 1000x, a typical metallurgical microscope has a NA of 1.25. This leads to a typical depth of focus of 0.3 microns [1] or \(3 \times 10^{-7}\) meters. Therefore, for a specimen to be considered “optically flat” at 1000x, the vertical deviation of the surface must not exceed 0.3 microns. Larger deviations will cause part of the image to appear out of focus.

1.5 Problem Statement

Our challenge is to design a device that allows any operator to produce optically flat specimens on a consistent basis. This device must keep the axis of the specimen perpendicular to the platen and allow the specimen to use the entire abrasive surface.

Because different materials require different treatment during polishing, our goal is to preserve operator influence on process variables. Giving the operator control of applied pressure, travel speed, and cycle time makes our device adaptable to all potential material polishing needs. Designing a guide fixture instead of a complete polishing system allows us to reduce cost and reach an untapped market of labs with manual polishing machines.

The following report details the progress of the design project. It contains an investigation into the current art of polishing technology, the planning schedule for the project, our design goals, and the resulting design concepts. The report outlines two final design concepts, and our reasons for choosing one concept for prototyping. The report includes detailed explanations and engineering drawings for the final design, and a bill of materials for the prototype.
2. Design Schedule

The design, construction, and evaluation of the polishing attachment is constrained to a five-month timeframe. This project involves the development of the design from the initial problem statement to a finished, working prototype. Because of this short timeframe, good planning is essential to project success. In addition to the delivery of the finished prototype, the design team is required to prepare four project reports and formal presentations, which identify the progress made in the development of the product.

Figure 2-1 shows the project plan for the polishing attachment design. Included on the plan are the stages in the design process that have already been completed:

- interpreting the problem statement
- generating and evaluating concepts
- completing a final product design
- developing and building a prototype
- assembling the prototype
- testing and evaluating the prototype
- identifying recommendations based on the test results
- beginning the patent application process
- preparing representative marketing material which could be used to advertise the attachment and its usefulness

All of these goals have been completed as of May 26th.

Figure 2-2 shows the project plan for deliverables for the end of the second quarter of work; these deliverables include reports, presentations and an executive summary. The design team must adhere to this schedule in order to complete all of our goals and to present our work in a professional manor.
Figure 2-1: Polishing Attachment Project Plan

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<td>System B Model and Analysis</td>
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<td>15</td>
<td>Modify final design</td>
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<td>Prototype Development</td>
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<td>Send parts out for machining</td>
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<td>Finish pieces</td>
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<td>Evaluation and testing</td>
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<td>Prepare test plan</td>
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Project: Polishing Attachment Project  
Date: Sun 5/31/98
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</tbody>
</table>

Figure 2-1: Polishing Attachment Project Plan

- Group [5]
Figure 2-2: Polishing Attachment Deliverables
Second quarter

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mid-quarter report</td>
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<tr>
<td>12</td>
<td>Prepare mid-quarter presentation</td>
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<tr>
<td>16</td>
<td>Prepare executive summary</td>
</tr>
<tr>
<td>17</td>
<td>Prepare first draft</td>
</tr>
<tr>
<td>18</td>
<td>Revise &amp; produce final draft</td>
</tr>
<tr>
<td>19</td>
<td>Final quarter report</td>
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<td>20</td>
<td>Revise mid-quarter report</td>
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<td>21</td>
<td>Prepare sections</td>
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<tr>
<td>22</td>
<td>Prepare intro/conclusion</td>
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<tr>
<td>23</td>
<td>Collate report</td>
</tr>
<tr>
<td>24</td>
<td>Prepare letter of transmittal</td>
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<tr>
<td>25</td>
<td>Revise and edit report</td>
</tr>
<tr>
<td>26</td>
<td>Prepare final presentation</td>
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<tr>
<td>27</td>
<td>Prepare individual sections</td>
</tr>
<tr>
<td>28</td>
<td>Prepare visuals</td>
</tr>
<tr>
<td>29</td>
<td>Practice and revise</td>
</tr>
</tbody>
</table>

Project: C
Date: Sun

Task Progress
Milestone
Summary
3. Market Survey

The study of existing products in the metallographic preparation field provides invaluable information for the design process. This study revealed information regarding equipment typically used in the polishing process including standard dimensions, wheel speeds, and configurations. Additionally, the benchmarking of existing commercial products creates an appreciation of the latest industry solutions while exposing opportunities to improve upon the current technology. The results of the market survey indicate that no current solution is universal, inexpensive, and simple to operate. This section summarizes the information found during the market survey; details on many of the available products found appear in Appendix A.

Grinding and polishing wheel diameters in industry range from seven to twelve inches, and many models have two of these wheels on one machine. However, eight inches prevails as the industry standard. Speeds of the wheels are variable and generally range from 10 to 600 RPM. Motors on these devices are generally within the 1/4 to 1 HP range. Water spouts and removable splash rings are usually standard. Additionally, most grinding/polishing machines offer the attachment of an expensive automatic polisher made by the manufacturer of that machine. These attachments range in cost from approximately $3000 to $6000. In some cases, modifications can be made to these attachments to allow for the use on other machines at an additional cost. These companies warn that mounting their devices to other machines can result in a loss in accuracy and precision of the sample’s surface finish.

Positioning device kits provided by Buehler only mount to Buehler machines and are used for lapping and cross sectioning rather than polishing. Both kits are expensive at over $1500 because they involve precision weights and motorized parts [2]. The workstation kit from South Bay Technology costs approximately $1500 and only mounts to one polisher model from the company. The $600 Struers specimen holder is not universal because it requires different models to accommodate different specimen sizes. Also, the holder is hand-held by the technician and, therefore, open to imperfections. While these kits are potential solutions, they are too specific and too expensive to be answers to the design problem at hand. The ideal product should be universal to all manual grinding/polishing machines and specimen sizes and should have high parallel
accuracy at a reasonable cost. This product study provided market awareness that further promoted understanding of the problem and the design issues involved. We found that eight-inch diameter polishing wheels are the industry standard; consequently, space for complex devices is extremely limited. With the non-uniformity of the shapes and materials of the machine housings, the mounting possibilities are also restricted. Potential competition for this device is limited to high-cost, brand-specific solutions. This indicates that a robust market exists for a low-cost precision grinding and polishing aid capable of adapting to multiple platforms.
4. Patent Search

A search performed on all patents issued after 1971 yielded several related documents. These patents can best be organized into three distinct groups:

- Patents for devices used to hold metallographic specimens onto a polishing wheel, which are directly applicable to the design problem.
- Patents featuring automatic polishing devices for metallographic specimens that demonstrate alternate methods for produce a mirror-finished surface.
- Patents related to polishing processes that are relevant as background information.

This section summarizes the results of the patent search; individual patents from all three groups are summarized and discussed in Appendix B.

Patent research shows many potential solutions to the problems inherent in metallographic polishing. These designs, at a minimum, include mechanisms for holding metallographic specimens against a standard polishing wheel. Many devices also feature methods for applying a fixed amount of force to the specimen, and ways of holding the specimen at the proper angle to the wheel. While these patents appear clever and apparently would function as intended, there are several drawbacks to each of these devices. For the most part, the devices described in Appendix B are complex, featuring precision moving parts and electronic devices that would exceed our intended price range. Perhaps the best argument against the usefulness of these patents is that nearly all, according to our information, have not yet been manufactured in quantity.

Thus, a simple, universal, inexpensive solution for current metallographic preparation nuisances has not been patented. The application of engineering knowledge and the design process will allow us to produce a successful, marketable product that fits a niche passed over by currently manufactured solutions.
5. Problem Analysis

Because the problem statement does not explicitly state all of the requirements for this design, the design team performed an analysis of the problem specifics. This investigation revealed the requirements and specifications for this design. These specifications can be broken down into six different groups and then rated in order of importance. Understanding the importance of the requirements and specifications allowed us to split the design problem into functionally oriented components for concept generation.

5.1 Design Specifications

There are several categories for design goals for the polishing attachment design. These categories, as defined by Ullman, include:

- Function and performance requirements
- Physical requirements
- Safety requirements
- Operation concerns
- Resource requirements
- Human factors

(Adapted from Ullman, p. 109) [3]

The specific requirements identified for this design are listed in Table 5-1 (found on the following page). An in-depth explanation and evaluation of these criteria can be found in Chapter 7. These requirements were rated from a 10, indicating critical importance, to a 1, indicating minimal importance. Function and performance issues earned the highest merits with manufacturing and appearance concerns being the least important.

The most important requirement for this or any design is that it fulfills its design intent. The polishing attachment’s primary function is to allow unskilled users to produce polished metallographic samples comparable to samples produced by skilled technicians. This requirement can be broken into several equally important stipulations. An experienced technician is able to keep the specimen flat to the polishing surface by minimizing rocking and edge rounding; therefore, the design must have a method for similarly maintaining the surface perpendicular to the wheel. The device must also allow for the specimen to be moved linearly against the wheel as a technician currently would
move the specimen. The operator of the device should be able to inspect the specimen in order to measure the progress of the polishing. The device should be functional for the range of wheel speeds currently used. The attachment also must allow the operator to easily change the sheet of polishing paper on the wheel. All of these stipulations should allow an unskilled operator to consistently produce usable specimens.

Table 5-1. Polishing attachment design requirements and importance

<table>
<thead>
<tr>
<th>Design requirements</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function and performance requirements</strong></td>
<td></td>
</tr>
<tr>
<td>Holds specimen perpendicular to polishing wheel without rocking</td>
<td>10</td>
</tr>
<tr>
<td>Allows for radial polishing motion</td>
<td>10</td>
</tr>
<tr>
<td>Allows easy inspection of specimen</td>
<td>10</td>
</tr>
<tr>
<td>Allows for varying polishing wheel speeds</td>
<td>10</td>
</tr>
<tr>
<td>Allows for operator to change polishing paper</td>
<td>10</td>
</tr>
<tr>
<td>Produces consistent, usable specimens</td>
<td>10</td>
</tr>
<tr>
<td><strong>Physical requirements</strong></td>
<td></td>
</tr>
<tr>
<td>Can attach to different polishing machines</td>
<td>9</td>
</tr>
<tr>
<td>Does not trap grit</td>
<td>8</td>
</tr>
<tr>
<td>Does not contaminate polishing surface with larger particles</td>
<td>8</td>
</tr>
<tr>
<td>Is sturdy</td>
<td>7</td>
</tr>
<tr>
<td>Resists vibration</td>
<td>7</td>
</tr>
<tr>
<td>Does not trap polishing rinse water</td>
<td>7</td>
</tr>
<tr>
<td>Resists abrasion</td>
<td>7</td>
</tr>
<tr>
<td>Resists corrosion</td>
<td>5</td>
</tr>
<tr>
<td><strong>Safety requirements</strong></td>
<td></td>
</tr>
<tr>
<td>Is entirely safe</td>
<td>8</td>
</tr>
<tr>
<td><strong>Operation concerns</strong></td>
<td></td>
</tr>
<tr>
<td>Attaches easily to wheel</td>
<td>6</td>
</tr>
<tr>
<td>Detaches easily from wheel</td>
<td>6</td>
</tr>
<tr>
<td>Cleans easily</td>
<td>6</td>
</tr>
<tr>
<td>Is easily maintained</td>
<td>4</td>
</tr>
<tr>
<td><strong>Resource requirements</strong></td>
<td></td>
</tr>
<tr>
<td>Costs between $500 and $1000</td>
<td>4</td>
</tr>
<tr>
<td>Incorporates standard parts</td>
<td>2</td>
</tr>
<tr>
<td>Requires standard tools for manufacture</td>
<td>2</td>
</tr>
<tr>
<td>Requires standard tolerances for manufacture</td>
<td>2</td>
</tr>
<tr>
<td><strong>Human factors</strong></td>
<td></td>
</tr>
<tr>
<td>Is easily controlled and used</td>
<td>6</td>
</tr>
<tr>
<td>Allows easy specimen change</td>
<td>6</td>
</tr>
<tr>
<td>Has attractive appearance</td>
<td>4</td>
</tr>
</tbody>
</table>

*Importance ranked from 10 (most important) to 1 (least important)*
In addition to the functional requirements, several physical requirements exist, most related to the environment surrounding the device. First, because this device must attach to a polishing wheel that the customer already owns, it should be sized in order to mount properly on the wheel and/or case. In mounting to the wheel, the device should not interfere with the polishing machine’s operation. Additionally, the polishing attachment should not trap grit which could contaminate higher grade polishing paper, introduce particles which may contaminate the polishing surface, nor prevent the rinse water from clearing the wheel of polishing debris. Finally, despite the fact that a polishing wheel operates at a significant speed, the attachment must be precise; vibration, physical deformation, abrasion, or corrosion should not affect its operation. Of equal importance to the physical requirements is the stipulation that the device operates safely despite any moving parts it may contain.

Concepts that meet the above requirements can be evaluated and improved by investigating how well they meet other lesser requirements, including:

- ease of attachment and detachment
- ease of cleaning and maintaining
- ease of operation
- ease of manufacturing
- retail cost

The target retail price for our manufactured device is currently $500, but it can be increased to $1000 for high-quality solutions. If the market price is any higher, customers might be better served either by buying an automatic polishing system or continuing to polish specimens without the aid of our device.

5.2 Subsystem concepts

The design must fulfill the functional and physical requirements because these are the most important to the success and acceptance of the design. The design problem allows consideration of distinct subsystems that allow for the required functions to be achieved when assembled. In order to facilitate concept development the proposed solution has been split into three distinct functional components. The first is a device to hold the polishing specimen against the wheel: the holder. The second is a mechanism to
constrain specimen motion parallel to the wheel face: the traveler. The third system prevents the specimen and the device from being moved: the mount. Although for some concepts these components may serve different functions, there are certain requirements that the various devices must meet. The requirements for each component are outlined in Table 5-2.

**Table 5-2. Polishing attachment design components and requirements for each**

<table>
<thead>
<tr>
<th>Component</th>
<th>Design requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Allows for varying polishing wheel speeds</td>
</tr>
<tr>
<td>All</td>
<td>Produces consistent, useable specimens</td>
</tr>
<tr>
<td>All</td>
<td>Does not trap grit</td>
</tr>
<tr>
<td>All</td>
<td>Does not contaminate polishing surface with larger particles</td>
</tr>
<tr>
<td>All</td>
<td>Resists abrasion</td>
</tr>
<tr>
<td>All</td>
<td>Resists corrosion</td>
</tr>
<tr>
<td>All</td>
<td>Is entirely safe</td>
</tr>
<tr>
<td>All</td>
<td>Is easily maintained</td>
</tr>
<tr>
<td>Mount</td>
<td>Allows for operator to change polishing paper</td>
</tr>
<tr>
<td>Mount</td>
<td>Can attach to different polishing wheels</td>
</tr>
<tr>
<td>Mount</td>
<td>Is sturdy</td>
</tr>
<tr>
<td>Mount</td>
<td>Resists vibration</td>
</tr>
<tr>
<td>Mount</td>
<td>Does not trap polishing rinse water</td>
</tr>
<tr>
<td>Mount</td>
<td>Attaches easily to wheel</td>
</tr>
<tr>
<td>Mount</td>
<td>Detaches easily from wheel</td>
</tr>
<tr>
<td>Mount</td>
<td>Cleans easily</td>
</tr>
<tr>
<td>Holder</td>
<td>Holds specimen perpendicular to polishing wheel without rocking</td>
</tr>
<tr>
<td>Holder</td>
<td>Allows easy inspection of specimen</td>
</tr>
<tr>
<td>Holder</td>
<td>Allows easy specimen change</td>
</tr>
<tr>
<td>Traveler</td>
<td>Allows for polishing motion that uses entire wheel</td>
</tr>
<tr>
<td>Traveler</td>
<td>Is easily controlled and used</td>
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</table>

5.3 Concept Generation

The functional requirements for the device have defined three components that will be required in any complete solution. Concepts for these three components are detailed in Appendix C. Each version of these component concepts may combine in several ways to form different final solutions. The development of several concepts for each component allows the freedom to create many final designs.
6. System Development

By combining the subsystem concepts described in Appendix C, we have narrowed our choices to two different systems. The features incorporated in both systems enable each to meet all of the functional requirements. The first system mounts to the wheel itself and uses three wheel bearings with an anti-rotation device to maintain a parallel system. The second system is a device that mounts on the casing of the polishing wheel and achieves its accuracy through an adjustable spherical bearing. These two systems will be analyzed in detail in order to identify the optimum problem solution.

6.1 Platform Mounted Design

One possible configuration for the polishing machine attachment is a case mounted device. This concept is illustrated in Figures 6-1 and 6-2. This design rests on the casing of the polishing wheel with three adjustable leveling feet. Magnets, mounted posts, or hook and loop fasteners hold down the platform. In this device, a plain spherical bearing with a split outer casing split creates the alignment to the wheel. The user pushes the specimen holder, without the specimen, through the slider and creates a perfect alignment with the wheel. When the holder is perpendicular, the device is locked into place with a toggle clamp.

With the holder aligned to the wheel, the specimen can be polished to mirror flatness. The user has the capability of pulling the specimen out of the alignment tube to check the progress at any time and also has the ability to index the specimen 90° by using the alignment tab and the slots in the tube. The inside of the tube has a sleeve bearing coated with a Teflon derivative that allows for a tight, low-friction fit.

The traditional device for holding a cylinder is a collet; one potential solution for gripping the cylindrical specimen uses this mechanism. Several other solutions, including a three point contact system, are also candidates for the final design. In either case, two different holders would be required to accommodate both 1” and 1¼” specimens. The specimen holder should detach from the overall holder to permit examination of the specimens under the microscope. This separation would allow for the holder to be used as the aligning tool for the spherical bearing.
The specimen must slide back and forth radially along the polishing wheel. A slider resting on a bearing surface accomplishes this task. As the slider will deform slightly when the locking clamp is tightened, a linear bearing and rail system would bind. The use of a sliding surface does not create interference in the mechanism. For this surface, a lubrication permeated bronze would work adequately provided the slider is secured from underneath to prevent separation from the track. A linear slide would be an elegant but costly solution, and could run the risk of binding. A Teflon coated surface would be also be acceptable, but wear and scratching from the abrasive slurry might degrade its performance over time.

This design is simple and flexible, allowing the user to have control over specimen alignment. Our major concerns center on the device weight and the accuracy of the alignment locking mechanism. The spherical bearing alone weighs approximately two pounds. If the device is too heavy a user will not be able or willing to put it back into position every time the emery cloth is changed. The locking mechanism is dependent on the user being able to apply significant force, enough to deform the slider and the outer bearing ring and thus eliminate angular movement. Finally, users will require some skill in order to use this device; training and practice will be essential to the production of quality specimens.
Figure 6-1. Platform Mounted Design
Figure 6-2. Exploded View of Platform Mounted Design
6.2 Rim Mounted Design

One way of assuring the perpendicularity of the specimen to the wheel involves the mounting of the entire device to the wheel itself. Figures 6-3 and 6-4 illustrate this design configuration. Our concept removes the rim that holds the sandpaper or emery cloth to the wheel, replacing it with a modified rim. The polishing attachment will travel on three cam followers that are keyed to a track on the inside of the rim. With this configuration, a user can attach an anti-rotation arm to any point on the case and the attachment will be stable and will stay perfectly parallel to the wheel.

The rim would be made of stainless steel and would have to be precision lathed. In addition to the track on which the cam followers will roll, the rim must also have drainage channels to let the water out; otherwise, the water could collect on the wheel. Initial tests indicate that even with a small amount of drainage, there is very little buildup.

The main body of the design has to incorporate many features in a small space. The cam followers must be mounted precisely and rigidly in order to preserve accuracy, but at the same time, one of the wheels must be adjustable so that the device can be assembled and wear can be compensated for. The anti-rotation arm must attach in a simple way, yet it has to be strong enough to keep the device from spinning under high speeds and high loads. The arm can be a rigid member as shown in the illustrations or a piece of hook and loop fastener that attaches to the case. The greatest challenge in the design of the body is providing enough room for the slider to use most of the surface of the wheel. By putting a radius on the face of the slider and a matching radius on the slot in the body, material is minimized and most of the polishing surface is utilized.

The specimen will be held by a device very similar to the holder described in the platform mounted concept. However, this holder will not need to adjust in the manner of the first design. The holder will ride in a slider that has an alignment tube with a Teflon linear bearing. The slider rides on four small linear sleeve bearings and along a pair of hardened rails, which allows effortless radial motion. This traveler allows the specimen to be inspected at any time and can also be rotated precisely 90° when necessary.

This concept relies more on careful machining and design than on human talent for its precision. However, the nature of the design poses both safety and mechanical
questions. The user will have to be well protected from getting a finger or loose clothing caught between the cam followers and the rim. There are also some potential problems with vibration and noise. Polishing wheels can spin up to 500 RPM, which means that the cam followers can spin up to 4000 RPM. At this speed, the noise could be very disconcerting, and the cam follower’s life could be significantly limited. The manufacturing of this device will be relatively simple with the exception of mounting the inner end of the rails. These holes could not be drilled simply due to their distance from an outer edge. Because of this, a block or insert of some sort would be needed to secure this inner end.

![Rim Mounted Design](image)

**Figure 6-3. Rim Mounted Design**
Figure 6-4: Exploded View of Rim Mounted Design
7. Final Design Selection

Both prototype concepts were designed to repeatably produce optically flat specimens. To determine which is the best overall design, an in-depth analysis of each of the design criteria is necessary. Analyzing the two different concepts with respect to each individual design requirement, the team was able to better understand the strengths and weaknesses of each design. The final design was selected through the use of a design matrix, which allowed the team to quantitatively judge the results of the design criteria analysis. This design matrix allowed us to select the frame-mounted design as the best design for prototyping.

7.1 Decision Matrix

In order to determine which of the two designs to further develop, the design team developed a decision matrix incorporating design requirements, advantages and disadvantages of each design. The matrix lists each design requirement with its relative importance, ranging from 10 as the most important to 1 as the least important. The team then compared the two designs based on each requirement. If one design was clearly superior, it received an ‘X’. If both designs met the requirement in a similar or equal manner, an ‘S’ was given to both designs. The matrix shows the total number of X’s for each design, as well as a weighted total, calculated based on the importance value for each requirement. The complete decision matrix is shown in Figure 7-1. Based on the results in this matrix, the design team chose the design with the highest for further development.

The design matrix features the functional requirements developed in the problem analysis. The requirements were divided into several categories, including:

- Function and performance requirements
- Physical requirements
- Reliability requirements
- Life-cycle concerns
- Resource requirements
- Human factors
Each requirement in the six categories was examined in detail, as described on the following pages.

Table 7-1 Polishing Attachment Design Matrix

<table>
<thead>
<tr>
<th>DESIGN REQUIREMENT</th>
<th>WT.</th>
<th>RIM</th>
<th>FRAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function and performance requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holds specimen perpendicular to polishing wheel without</td>
<td>10</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Allows for radial polishing motion</td>
<td>10</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Allows for easy inspection of specimen</td>
<td>10</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Allows for various polishing wheel speeds</td>
<td>10</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Allows for operator to change paper</td>
<td>10</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Produces consistent, usable specimens</td>
<td>10</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Physical requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Can attach to different polishing machines</td>
<td>9</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Does not trap grit</td>
<td>8</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Does not contaminate polishing surface with larger partic</td>
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NOTE: 'X' INDICATES A SUPERIOR DESIGN, WHILE 'S' INDICATES THAT EACH DESIGN MEETS THE REQUIREMENT EQUALLY WELL.
7.1.1 Functional Requirements

The first set of requirements involves the function and performance of each design. These requirements are crucial to the design and thus have importance ratings of '10.' The first requirement and the most important is the ability of the design to hold the axis of the specimen perpendicular to the face of the polishing wheel. Since the frame design allows for adjustment of the specimen axis, it ensures that the specimen will always be suitably perpendicular. With the rim design, the perpendicularity would be achieved using tight manufacturing tolerances, which may or may not prove feasible. Thus, the frame design was considered to be superior with respect to this requirement. The next three requirements of allowing for radial polishing motion, inspection of the specimen, and varying of polishing wheel speed are met in similar fashions for both designs and thus, neither design was deemed superior. The next requirement involves the ability of the design to allow the operator to easily change the grinding paper. For both designs, the device must be removed from the grinding machine. The rim design is simply lifted from the wheel, while the frame design is semi-permanently attached in some fashion and, therefore, more difficult to remove. In this case, the rim design was superior. The last requirement in this category demands that the design produce consistently optically flat specimens. Both designs meet this specification.

7.1.2 Physical Requirements

The next category of design conditions deal with physical requirements, which range in importance from 5 to 9. The first requirement is the ability of the design to attach to different polishing machines. The rim design attaches directly to the platen of the machine, which is nearly universal. The frame design, on the other hand, attaches to the housing of the machines, which vary in size, shape, and material from unit to unit. For this reason, the rim design is superior due to its ability to fit all machines regardless of housing configurations. The next two requirements deal with the prevention of trapping grit and transferring that grit to other papers. The frame design sits far enough away from the wheel as to not be contaminated by the slurry or grit that could cause contamination. Because the rim design sits on the platen, it has a greater chance of entrapping any contaminants. Therefore the frame design is superior in this respect. The next three requirements include the sturdiness, vibration resistance, and wear resistance
of the design. The frame design is static and can be made to be as large or thick as needed, while the rim design has parts spinning at high speeds and is constrained to fit on an eight-inch platen. In this way the rim design is more exposed to potential problems including vibration and wear which make the frame design superior. The next two requirements are satisfied by both designs. Both concepts allow the flushing of the rinse water and both can be made of corrosion resistant materials.

7.1.3 Safety Requirements

The next requirement is the overall safety of the device, which was given an importance rating of 8. Because the frame design is static and semi-permanently attached to the housing, it is considered to be safe. As stated previously, the rim design has components that spin at high speeds and is not rigidly attached to the machine, which leaves the possibility of injury. For these reasons, the frame design is superior with respect to safety.

7.1.4 Operation concerns

The next category of requirements is operation concerns, which range in importance from 4 to 6. The first two involve how easily the device attaches or detaches from the machine. The rim design is easily lifted on or off of the platen, while the frame design is semi-permanently attached. The rim design is, therefore, superior for these requirements. The next two conditions involve how easily the device is cleaned and maintained. Because the frame design is not in contact with the slurry and does not have any moving parts, it is virtually maintenance-free. The opposite is true for the rim design, as it would require frequent cleanings and lubrication. The superior design in this case is the frame concept.

7.1.5 Resource requirements

The following design provisions deal with resource requirements that range form 2 to 4 in importance. All requirements are based on the cost and manufacturing characteristics such as standard parts, tools, and tolerances. Currently, the budget for building a prototype is limited to $400. The frame design is relatively simple in that it has few parts, can be easily manufactured, and has standard tolerances. On the other
hand, the rim design has several expensive parts, is difficult to machine, and must hold
tight tolerances. A quick cost analysis estimated the cost of the frame design to be
around $300, while the rim design was in excess of $500. Based on these economic
reasons, the frame design is superior.

7.1.6 Human factors

The last category of requirements includes human factors, ranging in importance
from 4 to 6. The first condition is the ease of operation. For the rim design the device is
put on the platen and is ready for use without any adjustments. In contrast, each time that
the frame design is put on the machine, it must be clamped down and re-aligned. The rim
design in this case is easier to operate than the frame design. The next requirement deals
with the ability of the design to allow for the easy removal of the specimen. Both designs
achieve this action in the same fashion. The next factor is the product’s appearance. The
team felt that neither design was clearly dominant in this respect.

7.2 Summary of Matrix Results

The decision matrix is an evaluation method that tests the completeness and
understanding of requirements, identifies the strongest candidate, and helps foster
improvements. Using all of these considerations, the design matrix produces a total of 13
points for the frame design, compared to 5 for the rim design. Calculation of the
weighted totals also favored the frame design 75 to 37. These numbers are somewhat
deceiving because the rim design is not necessarily as inferior as the matrix indicates. If
the space were not as constrained, or resources were not an issue, the results may have
been much closer. For the purposes of this project, however, those requirements are
important and the frame design emerges as the most feasible candidate for development.
Using the knowledge gained from this process, the design team has chosen to further
refine the frame design in order to produce the most successful device.
8. Redesign for Prototyping

Although the decision matrix indicated that the concept of a case-mounted frame was superior, a subsequent analysis of the case-mounted design raised several serious issues with the interface and the mounting system. The current case design:

- does not allow the user to orient the device, forcing them to use a potentially uncomfortable travel motion
- is potentially unstable when mounted in some case configurations
- causes difficulties in changing the paper, due to weight and space considerations

All of these issues stem from the mount subsystem, and all can be attributed to the challenge of mounting to the cases of many different platforms. In order to remove the restriction that caused this difficulty, we concentrated on the most common polishing system configuration, that of a square case with a 10.5” diameter splashguard well.

Instead of mounting to the case itself, we elected to replace the splashguard on the existing system with our polishing attachment. Because the splashguard is rotationally symmetric, our device can be oriented in any direction with respect to the case for user comfort.

In addition, this mounting scheme is much simpler than the previous three-point mount. Using three clamps positioned around the splashguard hole, our frame can be fixed with a simple, easy-to-secure connection. This reduces the number of steps for removal and thus the complication of paper replacement.

These simple redsizns to the case-mounted frame concept address the major shortcomings of that design while preserving its advantages. These changes also have no real impact on prototype cost.
9. Refined Polishing Attachment Design

This section describes the components of the final design for prototyping, which is an enhanced version of the previous case-mounted design. It includes three separate subsystems: the holder, the traveler, and the mount. These subsystems are illustrated in Figure 9-1. Formal engineering drawings and a bill of materials for all of the components in this design are contained in Appendix D.

![Exploded View of Polishing Attachment](image)

Figure 9-1. Exploded View of Polishing Attachment

9.1 Holder Subsystem

The holder subsystem depicted in Figure 9-2 includes the main holder and the removable specimen mount. The main holder consists of the holder body, the retaining screw, the knob, the indexing pins, the e-clip, and the alignment pin. The removable specimen mount is composed of the receptacle, the specimen, and a setscrew.
The holder body is a turned piece of aluminum, hollowed out to reduce weight. Two 1/8-inch diameter dowel pins press-fit into the bottom serve as the indexing pins. An additional ¼ inch dowel pin press-fit into the side of the holder body functions as an alignment pin.

The stainless steel retaining screw is threaded into the plastic knob and secured with a commercial thread-locking adhesive. The opposite end of the retaining screw is secured through the holder body by means of an e-clip. This permits a sliding fit of the retaining screw through the holder body without allowing the parts to separate.

The setscrew is threaded into the wall of the aluminum receptacle. To secure a specimen, the user places it in the receptacle and tightens the setscrew with the provided Allen wrench until the specimen is gripped securely.
The solid alignment of the receptacle to the holder body is accomplished by means of the retaining screw. The user inserts the indexing pins of the holder into the matching holes in the receptacle and turns the knob to lead the retaining screw into the receptacle. Removal of the receptacle is accomplished by reversing the procedure. Figure 9-3 illustrates the fully assembled specimen holder.

Figure 9-3. Assembled Specimen Holder

9.2 Traveler Subsystem

The traveler subsystem consists of the clamp housing, the clamp latch, the spherical bearing, the bearing sleeve, and four slide plugs, as shown in Figure 9-4, and in the assembled views in Figure 9-5 and 9-6 (following page).
A machined piece of 6061 aluminum with four tapped holes, a center hole, and a slot forms the clamp housing. The bearing sleeve is a Pacific Bearing Frelon sleeve bearing with slots machined into the upper edge. A heavy-duty Southco over-center draw latch functions as the clamp latch. The slide plugs are stock Pacific Bearing adjustable bearing plugs, firmly set in the tapped holes with a commercial thread-locking adhesive. The spherical bearing is an SKF two-inch inside diameter spherical bearing with a slot cut in the outer ring.

The bearing sleeve is press-fit into the spherical bearing, which in turn is secured to the clamp housing with an adhesive. The clamp latch is mounted to the clamp housing with screws.

Adjustment of the spherical bearing is possible when the clamp latch is open. Drawing the latch shut serves to squeeze the sphere in the bearing enough to prevent motion. The bearing plugs protrude slightly from the base of the clamp housing to
provide a low-friction sliding surface. The bearing sleeve allows the shaft of the specimen holder body to slide freely in either open or clamped position. The machined slots in the upper edge hold the alignment pin securely and thus prevent rotation.

![Figure 9-5. Assembled Top View of Traveler](image1)

![Figure 9-6. Assembled Bottom View of Traveler](image2)

9.3 Mount Subsystem

The mount subsystem consists of the mount frame, two bearing plates, two travel stops, and three holding latches, as shown in Figure 9-7.
The mount frame is a machined piece of 6061 aluminum with one slot cut to allow for specimen travel, and three holes cut to reduce weight and allow water to flow. A ridge on the underside of the plate fits into the standard size wheel well on the polishing machine. The bearing plates are pieces of hardened and ground 17-4 stainless steel, secured to the mount frame with recessed screws. The travel stops are small bumpers made of compliant elastomer fixed to the mount frame. The holding latches are Southco over-center draw latches.

The holding latches are mounted to the case of the polishing wheel with adhesive pads. Spongy felt rings adhered around the bearing plugs would brush particulates away from the travel surface as the plugs ride on the hardened bearing plates.

To attach the mount, the user sets the polishing attachment into the splashguard well in the polishing machine and clips down the three holding latches. Removal is as
simple as the release of these latches and the lifting of the bearing plate from the polishing machine.

### 9.4 Overall Design

Figures 9-8 and 9-9 show renderings of the whole system put together.

![Assembled View of Polishing Attachment](image)

**Figure 9-8. Assembled View of Polishing Attachment**
Figure 9-9. Fully Mounted Polishing Attachment
10. Prototype Construction

To best test and evaluate our design, we developed and constructed a working prototype. The methods and materials used in this construction will not necessarily be those used in the production of a final, mass-produced product. This prototype needs only to simulate how this final product will operate, and allow us to identify any improvements that can be made in the final design. Similar to the concept generation phase, the prototype construction is organized into three distinct sections. These sections correspond to the construction of the subsystems discussed in Section 9: the holder, the traveler, and the mount. All drawings and descriptions of purchased parts that comprise the prototype appear in Appendix D.

10.1 Construction of the Holder Subassembly

The holder subsystem can be broken down further into three components: the main holder, the specimen receptacle, and the aligning tool. The aligning tool consists of a 6061-aluminum rod, turned down to a diameter of 1.75 inches, 6 inches long. One end of the tool is faced off in a lathe to ensure that it is perpendicular with respect to the axis of the tool. The other end is rounded to provide comfortable, easy handling of the tool. The faced-off end is then bored out, leaving a 3/8” shoulder for surface contact. This lightens the tool and reduces the chances of misalignment. After the part is machined, it is polished and anodized to protect the surface from scratches and corrosion. Figure 10-1 shows a photo of the finished aligning tool.

Figure 10-1. The Aligning Tool
Similar to the aligning tool, the specimen receptacle is a 6061 aluminum rod, turned to a diameter of 1.75 inches. The receptacle is ¾" long and has a recess machined into one face to hold the specimen. The recess geometry is CNC-machined and is designed to hold the specimen on two faces and to leave room for error in the size of the specimen. The specimen is held with a small 10-32 setscrew that enters the recess from the side. The other face is machined flat with two 1/8" holes drilled to accept the alignment pins on the main holder. These holes are placed 180 degrees apart from center at a radius of 0.625 inches. A hole is drilled and tapped ¼-28 through the center of the part to receive the retaining screw from the main holder. The specimen receptacle is also polished and anodized to reduce the effects of corrosion and wear.

The specimen holder consists of four parts. The first is the polyurethane ball that serves as the knob. The ball was clamped into the chuck of the lathe and a 1 ¾ inch diameter hole was bored into it. The knob has a ¼-28 hole tapped in the center to receive the retaining screw, a ¼-28 threaded stainless rod cut to a length of 4 3/8 inches. This rod is glued into the knob. The holder body was made out of a 6061 aluminum rod turned down to a diameter of 1.75 inches, 4 inches long. The body was then hollowed out by boring a 1.5 inch diameter hole 3.5 inches deep. Through the remaining ½ inch, a ¼ inch hole is drilled to allow the passage of the retaining screw. On the end of the holder, two 1/8 inch holes, 180 degrees and 0.625 inches from the center were drilled, ¼ inches deep. 1/8-inch diameter dowel pins were pressed into these holes. These pins provide alignment by fitting snugly into the holes drilled into the specimen holder. On the side of the main holder, near the knob, a ¼ inch hole was drilled, and a dowel pin was pressed into it. This pin will rest in the notches cut into the bearing sleeve of the traveler and allow the user to index the holder in 90° increments. The main holder is polished and anodized. The knob and retaining screw are inserted into the holder body, and a circular clip is slipped over the threads to allow the retaining screw to be retracted and to keep the knob from separating from the holder body. Figure 10-2 on the following page shows a photo of all the holder parts.
10.2 Construction of the Traveler Subassembly

The two bearings that form the heart of the traveler subsystem must be modified to function properly. The spherical bearing casing requires a break to be compressed enough to inhibit any motion. Since the casing is hardened steel, and the split should be as small as possible to keep grit from entering the bearing, the 10-thousandths of an inch wide cut through the bearing casing is made by a wire electron discharge machine.

Four $\frac{1}{4}$ inch wide slots are milled $\frac{3}{4}$ of an inch lengthwise down of the linear bearing. These slots are machined $90^\circ$ apart and are designed to hold the indexing pin on the holder. The sleeve bearing is pressed into the spherical bearing.

The clamp housing of the traveler is machined out of a block of 6061-aluminum. This housing has a 3.188-inch hole bored through the center to receive the spherical bearing, and is split to allow it to close around the spherical bearing.

To close these splits and effectively lock the spherical bearing in place, a clamp had to be devised. There were several iterations during the design of the clamp. Our first alternative was a Southco toggle clamp. This type of clamp has ample strength to lock the bearing, but, it tends to snap shut. The question of whether or not this snap would cause the traveler to jump and disturb the alignment induced us to design a clamp with a smoother close. Our second alternative uses a piece of threaded rod to uniformly pull both sides of the traveler together. Both of the clamps were built and tested. The toggle clamp took very little effort to close and didn’t cause the traveler to jump at all. The screw clamp worked well, but it wasn’t as user-friendly and it could easily be over-
tightened. We elected to use the toggle clamp, slightly modified to keep the user from having to hook the two halves together.

The traveler slides back and forth on four bearing plugs. These plugs are threaded into through holes in the corners of the clamp housing. The plugs require an ultra-fine ¼-20 tap. Originally, the holes on the traveler were going to be left open. After initial construction, the team decided that the holes were a potential danger due to the sharp edges, and they also took away from the aesthetics of the design. To remedy this situation, a ¼” deep recess 1” in diameter is machined over the holes, and they are covered with PVC plugs that match the contour of the housing. The clamp housing is polished and anodized and the bearing plugs are precisely aligned and epoxied into place. Figure 10-3 shows a photo of the finished traveler with the clamp slightly opened.

![Figure 10-3. The Traveler Assembly](image)

10.3 Construction of the Mount Subassembly

The base plate of the mount is a complex shape, and must be CNC machined to guarantee its quality. The necessary data sets for the CNC process were exported from our SolidWorks™ modeling software in IGES format and sent electronically to the shop.
The shop’s technicians used their MasterCam™ milling software to interpret our IGES file and create the necessary Mfiles to machine the part. The plate is cut from a 12” x 12” x ¾” block of 6061-aluminum, and has been hand polished and anodized black.

The traveler slides on two hardened stainless steel rails. These rails are machined from a bar of 17-4 stainless and then heat-treated at 900°F for one hour and then air-cooled. The rails are then precision-ground on both sides and attached to the base plate for the final grind to ensure that they were perfectly flat to one another. They are secured to the plate from the underside by three 10-32 screws.

To smoothly stop the traveler and prevent jarring of the device, we investigated a wide variety of materials and options. Small elastomer bumpers were our final choice and they are each secured to the base plate with a 6-32 screw. Figure 10-4 shows a photo of the finished mount assembly.

Figure 10-4. The Mount Assembly

The polishing attachment is secured to the polishing machine with three Southco tie-down clamps. These clamps are held to the case with an adhesive backing and are
adjustable to ensure a firm grip on the mount. Figure 10-5 shows a photo of the fully assembled device and a standard polishing wheel.

Figure 10-5. The Polishing Attachment on a Standard Polishing Wheel
11. Device Operation

Because the polishing attachment device includes multiple components, the operation of the device may not be obvious to every potential user. A detailed set of operating instructions is necessary to ensure that any operator will use the device correctly and effectively. The first draft for these operating instructions is included in Figure 11-1, pp. 11-2 through 11-4.

The operation of this device can be broken down into several main steps:

1. Preparation of the device, the wheel and the specimen before polishing begins.
2. Aligning the axis of the holder sleeve to be perpendicular to the polishing wheel face.
3. Grinding the specimen face using the coarsest grit paper.
4. Repeating the alignment and the polishing for progressively finer grit paper.
5. Inspecting the specimen under the light microscope.

Except for the alignment stage, these steps are similar to the procedure used for manually polishing a specimen, outlined in section 1.2.
Finally, an affordable alternative to tedious hand polishing...
...no more out-of-focus specimens!
Metallographic Specimen Polishing Attachment
Operating Instructions

Device Schematic

A - Specimen
B - Holder
C - Receptacle
D - Holder Knob
E - Alignment Pin
F - Alignment Tool
G - Traveler
H - Traveler Clamp
I - Traveler Sleeve
J - Base Plate
K - Bumper Stops
L - Polishing Machine
M - Polishing Wheel
N - Abrasive Paper
O - Paper Rim
P - Faucet
Q - Case Clamps

* - not included

Preparation

1. Insert 1" or 1 ¼" diameter specimen (A) into the correct receptacle (C). Turn set screw until specimen is locked in place.
2. Place coarse grit abrasive paper disk (N) on polishing wheel (M). Place paper rim (O) on polishing wheel to hold paper.
3. Place attachment base plate (J) on the polishing wheel case, and rotate attachment so that traveler assembly (G) is oriented in a comfortable position for use. Rotate faucet (P) so that water stream will be directed onto the polishing wheel surface.
4. With device in a suitable configuration for polishing and for access to the water flow, lock case clamps (Q) to prevent polishing attachment base from rotating.

Alignment

5. Insert alignment tool (F) into traveler sleeve (I).
6. Apply pressure to the top of alignment tool downward onto the wheel to bring aligning face into complete contact with paper surface.
7. Lock traveler clamp (H) while the holder is held flat.
8. Remove alignment tool from sleeve.
Grinding and Polishing

9. Turn on the polishing wheel and set to suitable speed for grinding.
10. Attach specimen receptacle to specimen holder (B) and turn knob (D) until receptacle is secure.
11. Insert specimen holder assembly into holder sleeve. Take care to insert alignment pin (E) into one of the alignment slots in the traveler sleeve (I). Take note which alignment slot was used.
12. While applying moderate vertical pressure on holder knob, move the traveler assembly gently back and forth between the two bumper stops (K).
13. After at least two minutes, remove holder assembly and visually inspect for scratches uniformly aligned in one direction. If the scratches are all in the same direction, this polishing stage is complete. Proceed to step 15 below.
14. If the scratches are not clearly in the same direction, reinsert holder assembly into sleeve, while inserting alignment pin into the same alignment slot used previously.
   If the scratches are not easily visible, remove the specimen receptacle from the specimen holder and place receptacle under the microscope for inspection.

Changing to Finer Sandpaper

15. Turn off polishing wheel and water to faucet.
16. Unlatch case clamps. Remove the entire polishing attachment and set aside.
17. Remove the paper rim and the current polishing paper. Add the next finer grade paper and replace rim.
18. To prevent cross-contamination with coarse grit, rinse specimen, receptacle and alignment tool under faucet. Additionally clean bottom of plate and traveler.
19. Replace the polishing attachment on the case and lock case clamps.
20. Repeat steps 6 through 22, replacing with progressively finer grit paper until the smallest grit size is reached. Note that for each step the alignment pin should be placed in a different alignment slot from the previous polishing step at 90° from the previous step.

Diamond Polishing

21. Thoroughly rinse all detachable components of polishing attachment to remove debris. Rinse wheel completely.
22. Replace abrasive paper with polishing cloth. Prepare cloth as if for traditional hand method.
23. Attach base and align device as in steps 3-8.
24. Polish as above.
   Note: Even though this attachment is designed to minimize grit migration, the most suitable method to prevent coarse contamination is to use a dedicated device for each of the grinding and polishing processes.

Inspection

25. When finished with all grinding and polishing, remove specimen receptacle from holder and place under microscope.
### POLISHING ATTACHMENT PARTS LIST

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<td>Bearing Plate</td>
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Figure 11.1 Operating Instructions
12. Testing and Performance Analysis

A series of performance tests performed in May of 1998, document the actual utility of the polishing attachment. These tests were intended to provide information on three important questions:

- Does the attachment work as expected?
- Does the device produce quality specimens more consistently than manual polishing?
- How can the design and operation of the device be improved?

The test results documented in this section demonstrate the answers to these questions. Every specimen polished using the device proved to be usable by our definition; only 17% of the manually polished specimens were usable. The testing also provided further insight into the problems inherent with manual polishing and illustrated how our device nullifies these problems.

12.1 Test procedure

The five team members ran the first set of tests using the polishing attachment. The objectives of these tests included:

- To establish a set of test results that will determine the improvement in polishing quality obtained by using the device (as opposed to manual results).
- To refamiliarize the team with the difficulties of manually polishing specimens.
- To provide the team with experience with using our polishing attachment device.
- To use the team’s experiences to refine the preliminary operating procedure described in the previous section.

The preliminary tests consisted of team members independently polishing up to three specimens manually and three specimens using the device.

Once the operating procedure had been refined and potential problems identified by the preliminary testing, interested parties were allowed to further test the effectiveness
of our device. Scheduling difficulties prevented a full focus group from being assembled, but the several people did volunteer to assist by giving their impressions of the device.

Testing by the interested users fulfilled a different set of objectives than the preliminary testing. These objectives included:

- To establish potential problems that an operator may encounter while becoming familiar with the device.
- To establish potential improvements for the device.

### 12.2 Performance Measurement

Theoretically, a good metallographic specimen will have no facets or defects that could mar the image viewed under the light microscope. However, since the magnification of the microscope is so great, there may be regions on the specimen that are “good” (optically flat) and other regions where a facet boundary makes some of the image out of focus, as shown in Figure 12-1.

![Figure 12-1. Microscopic Image of Faceted Specimen](image)

We have defined a usable specimen as one which, when randomly sampled at ten distinct points on the specimen, appears to be “good” in at least eight of the locations.

### 12.3 Testing results

The Excel spreadsheet in Figure 12-2 on the following page features information regarding each polished specimen. This spreadsheet calculates the total percentage of “good” (optically flat) regions, as well as the proportion of usable specimens, from the specimens used in testing.
## Polishing attachment testing results

Indicate "1" as good sample point, "0" as poor sample point.

<table>
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<th>3</th>
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<tr>
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<td>17%</td>
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</tbody>
</table>

**Figure 12-2. Testing Data Sheet**

The test results indicate the following:

1. The polishing attachment device works. Every specimen polished using the device is usable, and only 4% of all views had some imperfection. This is remarkable because most of the testing was performed using specimens provided by Professor Blucher. These specimens are extremely difficult to polish because the metal specimen is much harder than the soft polymer that encloses the metal.
2. The polishing attachment significantly improves on the manual polishing procedure. Most of the team members are inexperienced with metallographic polishing; this is obvious in the results, as only 17% of the manually polished specimens were usable. Despite the team’s inexperience, specimens polished with the attachment were universally usable. This demonstrates that our device will significantly improve the efficiency of inexperienced polishers.

3. The alignment function of the attachment works as intended. This became obvious when Janelle Helser used the attachment to polish a specimen she had used in other research. When placed in the receptacle, the specimen, which had been polished once previously, was pitched at an angle of greater than 10° from the face of the receptacle. Using the alignment tool to lock the alignment to the wheel allowed Janelle to polish the specimen face until it was flat to the wheel. Later, using the same sample, we inadvertently neglected to realign the device after changing the polishing paper. The specimen began developing a facet immediately. By realigning the device, the facet was quickly removed.

4. The attachment also improves on other aspects of the polishing process. Some samples proved difficult to polish by hand because the wheel would tend to grab and pull at them at certain orientations. The attachment prevents the specimen from being moved by the wheel. The attachment also provided a much more comfortable grip for the user, and allowed the user to operate the wheel at higher speeds, further improving the throughput of the process.

The positive results gained by testing suggest that the polishing attachment would shorten the time required to produce specimens for viewing under the microscope. Inexperienced users have no trouble using the device to produce quality specimens. Even experienced polishers can find the device useful. Janelle Helser, who has polished many specimens during her research this year, said of the device: “I had doubts as to whether the ‘feel’ would be lost and if it was, how would that affect my polishing technique? [The] ‘feel’ was mostly lost, but it didn’t seem to matter. The samples came out fine anyway.”
13. Patent application

The team is currently in the process of applying for a patent for this polishing attachment device. The team members met with Richard J. McNeil, Northeastern University’s Director of Research Management and Technology Transfer, to discuss the necessary patent procedures and guidelines. At this meeting Mr. McNeil inquired about the novelty of the team’s design and its advantages over former approaches. Additionally, the team members and Mr. McNeil acknowledged the existence of potential commercial interests for companies or institutions that perform any type of metallographic specimen preparation.

After this initial meeting, the process to determine whether the university will financially support the patent application began. The design team filed the Patent Disclosure Application with the university in which the team members and Prof. Blucher were named as co-inventors. Appendix E includes a copy of this document. Upon receipt of the letter, a provisional patent may be filed until Northeastern University’s Patent Committee reviews the invention. The team presented details on the polishing attachment design to the 12 members of the Patent Committee at the May 26th meeting. If the committee does not favor the design, the university will file an affidavit of non-interest, and the team will pursue the patent either commercially or individually.

Presently, the Patent Committee is still reviewing the design and we expect to hear their decision during the first week of June 1998. In the end, it is the hope of the design team that carrying out the patent process will be educational, and with any luck, profitable.
14. Summary and Recommendations

Our polishing attachment development began as a problem statement and proceeded through multiple stages, specifically:

- problem investigation
- project planning
- market research
- patent research
- concept generation
- detailed concept development
- final design selection
- generation of engineering drawings and bill of materials for prototype
- prototype construction
- testing and evaluation
- patent application

The design process has led to a fully-functional prototype, which significantly improves the manual polishing procedure. Using this prototype, an operator can consistently produce optically flat specimens using the polishing wheel that he or she already owns.

The final design of the polishing attachment meets all of the established objectives and requirements. The attachment could be sold for to laboratories and research centers that cannot afford automatic or semi-automatic polishing systems.

Some potential improvements for the design would give the user feedback regarding the variables in the polishing process. A force sensor built into the holder assembly would indicate whether the force being applied to the specimen meets the recommended standard values. Electronic levels could be used to identify when the attachment has reached the proper alignment with the polishing wheel.

Further potential improvements include making the attachment more automatic than its current operation. The force sensor in the holder would activate a controller that could add to or reduce the force applied on the specimen. An electric motor or a pneumatic cylinder could move the traveler steadily back and forth along its path. These augmentations would be available in the deluxe version of the polishing attachment, which could retail for approximately $1,000, which is still considerably less than most automatic polishing devices.
15. References

References cited in appendices are listed at the end of the appendix and are not included here.

15.1 General References


15.2 References Cited


Appendix A: Product Study and Market Survey

The study of existing products in the metallographic preparation field provides invaluable information for the design process. Spatial constraints as well as other weight and mounting restrictions of the proposed device are defined through this process. Additionally, the benchmarking of existing commercial products creates an appreciation of the latest industry solutions while exposing opportunities to improve upon the current technology.

A-1. Product Study

Research into the metallographic area of manual microstructural preparation and analysis equipment, consumables, and accessories produced the names of six major companies. Two of the companies that offer appropriate equipment, Buehler Ltd. and Struers, produce most of the products on the market. Allied High Tech Products Inc., Leco Corporation, South Bay Technology Inc., and ImpTech are other manufacturers of standard metallographic preparation devices. While each company has a variety of different manual grinding/polishing products, the platforms and features are similar.

A.1.1 Buehler Ltd.

Buehler is considered by most engineers in the field of metallography as the industry leader. The company offers manual grinding/polishing machines with eight, ten, or twelve-inch diameter universal working wheels and removable splash rings. Machines with double eight-inch or ten-inch wheels are also offered. All models have waterspouts to cool and clean the wheel. The devices can operate at a fixed speed, usually 300 RPM, or at variable speeds ranging from 10 to 500 RPM, depending on the model. The speed of the wheel is held constant under all load conditions and is powered by a 1 HP motor. An optional semi-automatic polishing fixture is available for $4500 and only affixes to Buehler manual devices. [A1]

Buehler offers two parallel positioning devices as kits in addition to their machines. The first positioning aid, pictured in Figure A-1, stretches across and above the working wheel and is used for cross-sectioning integrated circuits. Priced at $1500, it offers precision angle adjustments, load flexibility, and quick removal and replacement of the
sample without the loss of the plane. The second apparatus, shown in Figure A-2, is a weighted micrometer-based lapping fixture that locks onto a corner of their grinder/polishers. This $1750 fixture is motorized to rotate the sample on the wheel while properly aligning the sample through the use of a fluid-filled mounting diaphragm. [A1]
A.1.2 Struers

Struers offers manual equipment with single or double wheels that range from seven to ten inches and also include twelve-inch diameters. All models have a waterspout and a removable splash ring. Fixed speeds are offered on some models at either 125 or 250 RPM, while the variable speed models range from 50 to 600 RPM. Most models also have an adapter for the attachment of an optional Struers semi-automatic polisher. The company features two devices that differ in the way that pressures are applied to the samples. Their $4300 semi-automatic polisher uses air pressure to accurately apply the force, while their $2900 model sacrifices some precision by using a less expensive spring system to apply the force. In addition, these attachments only fit certain models of Struers manual machines.

Furthermore, Struers provides a manual specimen holder for $600 that allows for an accurate depth to be ground from the specimen. The holder accommodates 29-30 mm (1.14-1.18 inch) samples and uses an adjustable, wear-resistant ceramic base to contact the paper when the preset depth is reached. As a result, planed, parallel samples are produced without facets.

A.1.3 Allied High Tech Products

Allied High Tech provides instruments with eight-inch wheels that have variable speeds from 10 to 500 RPM. Each model has a 1/4 HP motor that rotates the wheel at a constant high torque. A waterspout and removable splash ring are also standard. For approximately $6000 more, the company also offers an optional automatic positioning device to attach to their manual machine. At an additional cost, Allied offers to reconfigure their semi-automatic device in order onto mount to other companies’ specific machines.

A.1.4 Leco Corporation

Machines from Leco have eight, ten, and twelve inch wheels that spin at variable speeds to 600 RPM. Different models feature either a 1 or 2 HP motor that rotates the wheel at a constant high torque. As with other companies, the waterspout and removable
splash ring are also standard. A $6000 optional semi-automatic positioning device that attaches to their manual machines is also available.

A.1.5 South Bay Technology

South Bay Technology’s instruments have eight-inch wheels with variable speeds up to 1725 RPM. Each model has a 1/3 HP motor as well as the standard removable splash ring and water spout. The company also offers an optional workstation that only mounts onto their manual polishers. This workstation helps to position the sample perpendicular to the wheel and costs $1495.

A.1.6 Imp tech

Imp tech manufactures polishing machines with eight-, nine-, or twelve-inch diameter working wheels. Some of the eight-inch and nine-inch models offer two wheels. The devices can be operated at a fixed speed or at variable speeds up to 1400 RPM. The motor size for the eight and nine inch models is 1/2 HP, while the twelve-inch models operate with a 1 HP motor. All models have a waterspout, a removable splash ring, and the option to attach a $6000 Imp tech semi-automatic polisher.

A.2 Automated Polishing Systems

The goal of automated metallography preparation is to control the system parameters of the entire grinding and polishing operation. In most cases, the functions of the automatic attachment as well as the base grinder/polisher and fluid dispensing system are directed through a programmable memory. Typical automatic polishers, like that shown in Figure 3-3, control the force applied to the specimen(s), the time of the grinding/polishing cycle, the rotation direction of the specimen(s), and the wheel speed of the device. For example, Buehler’s semi-automated mechanism has the following specifications: a variable force application from 1 to 60 pounds, a variable timer up to 100 minutes, and specimen rotation at 30 RPM in either clockwise or counterclockwise directions. The utility of such systems is evident for repetitive work in which productivity and reproducibility are imperative. [A1]
Automation attempts to replace the human aspect of the preparation process while improving upon the overall quality of the work. In doing so, it allows for more than one specimen to be prepared at a time. Single samples may be done just as easily as three or even twelve. Certain devices can either apply a central pressure to the jig that holds the samples or to each specimen individually. This force is typically measured by electronic strain gauges that provide accuracy far beyond human capability. Some models automatically oscillate the specimens as some lab technicians would in the polishing process. The capabilities of automation not only save time but also increase the probability that each specimen will be polished in the same manner.

A.3 Results of Market Survey

Wheel diameters in industry range from seven to twelve inches and many models have two of these wheels on one machine. However, eight inches prevails as the industry standard. Speeds of the wheels are variable and range from 10 to 600 RPM in most cases. Motors on these devices are generally within the 1/4 to 1 HP range. Water spouts and removable splash rings are usually standard. Additionally, most grinding/polishing machines offer the attachment of an expensive automatic polisher made by the manufacturer of that machine. These attachments range in cost from approximately $3000 to $6000. In some cases, modifications can be made to these attachments to allow for the use on other machines at an additional cost. These companies warn that mounting their
devices to other machines can result in a loss of accuracy and precision of the sample’s surface finish.

The positioning device kits from Buehler only mount to Buehler machines and are used for lapping and cross sectioning rather than polishing. Both kits are expensive at over $1500 because they involve precision weights and motorized parts. The workstation kit from South Bay Technology costs approximately $1500 and only mounts to one polisher model from the company. The $600 Struers specimen holder is not universal because it can only hold samples of a certain diameter. Also, the holder is hand-held by the technician and, therefore open to imperfections. While these kits are potential solutions, they are too specific and too expensive to be answers to the design problem at hand. The ideal product should be universal to all manual grinding/polishing machines and specimen sizes and should have high parallel accuracy at a reasonable cost. [A1]

This product study provides market awareness that further promotes understanding of the problem. Currently, only six basic platforms exist for mounting our polishing fixture. Using the eight-inch diameter as a standard, space is limited. With the non-uniformity of the shapes and materials of the machine housings, the mounting possibilities are also restricted. Potential competition for this device is limited to high-cost, brand-specific solutions. This indicates that a robust market exists for a low-cost precision grinding and polishing aid capable of adapting to multiple platforms.

A.4 References

Appendix B: Patent Search

A search performed on all patents issued after 1971 yielded several appropriate documents. These patents can best be organized into three separate groups:

- Patents for devices used to hold metallographic specimens onto a polishing wheel which are directly applicable to the design problem.
- Patents featuring automatic polishing devices for metallographic specimens that demonstrate alternate methods for produce a mirror-finished surface.
- Patents related to polishing processes that are relevant as background information.

The following sections describe patents found from each of these groups, arranged in chronological order.

B.1 Patented Devices Used to Hold Metallographic Specimens onto a Polishing Wheel

The following patents apply to potential solutions to the design problem. They include a device or mechanism for holding metallographic specimens against a standard polishing wheel. Many feature methods for applying a fixed amount of force to the specimen, and ways to hold the specimen at the proper angle to the wheel.

B.1.1 Scan-Dia Polishing System

Patent number 3762103, “Machine for grinding and polishing metallographic and mineralogic samples”, was issued to Erling-Juul Nielsen of Scan-Dia, on October 2, 1973. This device polishes samples embedded in a body of synthetic resin, similar to specimens used in Northeastern’s Metallurgy Lab. The device is capable of polishing several samples simultaneously on the same wheel, while moving the samples linearly along the radius of the wheel (the preferred method for metallurgical polishing). This machine may be expanded to allow the samples to be conveyed automatically to successive polishing wheels, while rinsing the samples when changing disks. This device thoroughly demonstrates one solution to the design problem, and allows multiple samples to be polished simultaneously. Figure B-1 shows a schematic of the device. [B1]
B.1.2 VEB Rathenower Optische Werke Polishing System (1)

Patent number 3930343, "Device for mounting specimens", was issued on January 6, 1976 to Detlef Welsch and Horst Waschull of VEB Rathenower Optische Werke. Their device mounts a number of specimens above a polishing wheel, while allowing the frictional contact between the samples and the wheel to be manually adjusted. This device is very similar to patent #3762103, but is simpler in design and approach, as shown in Figures B-2 and B-3. [B2]
B.1.3 VEB Rathenower Optische Werke Polishing System (2)

Patent number 3931696, “Device for making sections for specimens and specimen supports therefore”, was issued to Wolfgang Lorenz and Heinz Strubig of VEB Rathenower Optische Werke on January 13, 1976. This design features a rotating polishing wheel with specimen supports above the polishing wheel. Of particular interest in this design is the scheme of the specimen support arms, the design of the supports which can hold specimens of cylindrical or conical cross section, and the means for adjusting the specimen location and angle on the polishing wheel. This patent is illustrated in Figures B-4 and B-5. [B3]

![Figures B-4 and B-5. VEB Rathenower Optische Werke Polishing System. Cross Section of Holder and Top View. [B3]](image)

B.1.4 Struers Polishing System

Patent number 4771578, “Apparatus for the grinding or polishing of workpieces”, was issued to Gert Jorgensen and Klaus Kisboli of Struers A/S, on September 20, 1988. As depicted in Figure B-6, this sample holder applies the pressure between the specimens and the polishing wheel through a system featuring a strain gauge. This system allows quantitative measurement of the pressures due to grinding and also allows the determination of the amount of sample that has been removed. [B4]
B.1.5 Barth & Cramer Holding Fixture

Patent number 5702293, "Holding fixture for metallographic mount polishing", was issued on December 30, 1997 to Clyde H. Barth and Charles E. Cramer of the U.S. Department of Energy. This device features an arm that holds a sample in place against the polishing wheel. The patent also features a method for applying and locking the pressure of the specimen against the wheel. [B5]
B.2 Patents Featuring Automatic Metallographic Polishing Devices

The patents in this section use nonconventional automatic methods to produce mirror-finished metallographic specimens. Most do not use a standard polishing wheel or polishing disks. These patents are a source of creative ideas that may be applied to potential solutions to the design problem.

B.2.1 Buehler Automatic Polishing Machine

Patent number 3906678, "Automatic specimen polishing machine and method", was issued to Kurt H. Roth of Buehler Ltd. on September 23, 1975. This device is diagrammed in Figures B-7 and B-8. This device features a non-rotating polishing head, against which the specimen is rotated and translated in order to achieve a polished surface. The speed of the motion and the loading on the device may both be changed while the device is operating. This patent shows how automated polishing may be achieved in a device which is considerably more expensive than our proposed design will be allowed to cost. This device is similar to the nonfunctional Buehler machine that is available in the Metallurgy Lab at Northeastern. [B6]

Figures B-7 and B-8. Buehler Automatic Polishing Machine and Details of Polishing Area [B6]

B-5
B.2.2. Jarrett Grinding Apparatus

Patent number 4343112, “Apparatus for grinding metallographic specimens” was issued to Tracy C. Jarrett on August 10, 1982. This automatic polishing machine, shown in Figures B-9 and B-10, features a vertically oriented grinding wheel and a rotating specimen holder. The grinding wheel is created with multiple grades of grinding wheels so that specimens may be polished by successively finer grit without changing the grinding paper. [B7]

Figures B-9 and B-10. Jarrett Apparatus for Grinding and Details of Specimen Holder [B7]
B.3 Patents Related to Polishing Processes

The patents assigned to this category may not be directly related to the polishing of metallographic samples; however, some aspect of the design highlighted in the patents could be applied to metallographic polishing and to the solution of the design problem.

B.3.1 Weber Polishing Machine

Patent number 3631634, “Polishing machine”, was issued on January 4, 1972, to John L. Weber. This patent describes a design for a polishing device that will hold a workpiece against a horizontal platen similar to a polishing wheel. This patent is applicable to our design problem because of the method the designer uses to hold the specimen to the wheel. The support structure is raised and lowered onto the wheel surface using pneumatics, but the appropriate pressure is applied between the specimen and the wheel through an adjustable dead weight. Application of an adjustable dead weight could be an appropriate method for the proposed polishing wheel attachment. [B8]

B.3.2 American Tool and Die Polishing Machine

Patent number 3813825, “Polishing machine or the like with a removable platen”, was issued to John L. Weber and George C. Klimas of American Tool and Die Corporation on June 4, 1974. This patent demonstrates another automatic polishing device with a workpiece supporting structure. This device allows for the polishing platen to be removed and replaced. This device demonstrates how the specimen support arm may be designed to allow for the changing of the polishing material underneath. [B9]

B.3.3 Toshiba Polishing Machine

Patent number 4593495, “Polishing machine”, was issued on June 10, 1986, to Hideo Kawakami, Shinchi Tazawa, and Masami Endo, of Toshiba Machine Company, Ltd. This patent features an automatic specimen polishing device. Although this patent is primarily concerned with the newly developed drive mechanism for this polishing device, the design also demonstrates a way of holding specimens in a top wheel structure and contacting them with a rotating polishing wheel. [B10]
B.4 Results of Patent Search

Patent research shows that similar ideas apply to potential solutions to the design problem. These ideas include a device or mechanism for holding metallographic specimens against a standard polishing wheel. Many devices feature methods for applying a fixed amount of force to the specimen, and also ways to hold the specimen at the proper angle to the wheel. While somewhat functional, these concepts are generally complex and not feasible using the present design of grinding/polishing devices. Moreover, none of these concepts have been acted upon beyond the patent phase.

The technology involved in specimen preparation is not complex; rather, it requires accuracy and precision. There is margin for a simple, universal, inexpensive solution to current metallographic preparation annoyances. The application of engineering knowledge and the design process has the opportunity to produce a successful, marketable product that fits a niche passed over by current manufacturing solutions.

B.5 References


Appendix C: Concept Generation

C.1 Definition of Functional Elements

Analysis of the design goals allows us to describe the functional elements of a solution. Any solution to specimen polishing misalignment must contain these fundamental elements in some form.

![Simplified Polishing System](image)

Figure C-1. Simplified Polishing System

C.1.1 The Holder

The first fundamental element maintains the perpendicularity of the specimen axis to the polishing disc. The holder prevents rotation of the specimen about any point to preserve surface parallelism. It also prevents rotation of the specimen about its z axis to preserve scratch mark orientation. The holder must fit all common specimen sizes. (1"-1¼" diameter, ½-1½" length) Additionally, if the other components of the polishing attachment do not maintain specimen orientation relative to the wheel, the holder must true the specimen.

C.1.2 The Traveler

The second fundamental element, the traveler, moves the specimen and the holder parallel to the face of the polishing disc to use the entire paper surface. It should move smoothly, and prevent the specimen from crossing the center of the disc.
C.1.3 The Mount

The third fundamental element prevents the traveler, holder, and specimen from spinning with the wheel. It must provide a rigid, vibration-resistant frame to withstand not only operating forces, but also incidental loads, both static and impact. The mount must fit all existing polishing machines.

C.2 Brainstorming

This stage of concept generation provided us with primitive forms of the simplified elements of our polishing attachment. To prevent becoming locked in to any one concept, we concentrated on producing a great quantity of independent solutions rather than a few polished ones. Our concept generation was purely based on function, not cost, manufacturability, or any other criteria. The later stages of the project will allow for the evaluation and refining of these concepts.

Table C-1. Holder Ideas

**maintain axis perpendicular to wheel face**
- vertical Teflon collar sliding fit, specimen internal
- vertical Teflon collar sliding fit, specimen external
- vertical collar bearing
- two vertical rails & collar bearings
- three vertical rails & collar bearings

**prevent axial rotation**
- key shaft
- indexing plate w/ keys
- sliding plate on three rails
- hold specimen (multiple sizes, removable for inspection)
- three-point contact grip (two rails & a point)
- rubber squeeze ring
- band clamp
- collet (hot press only)
- disposable (one-use) potting molds for cold-press

**indexing**
- removable holder w/ orientation details
- key shaft
- indexing plate

**orienting** (optional; depends on mount)
- ball-in-socket joint w/ locking plate
- nesting discs
- universal joint
Table C-2. Traveler Ideas

**Linear Motion System**
- two rails & linear collar bearings
- stock linear motion components
- keyed rail
- Teflon square-in-corner sliding fit
- hardened metal square-in-corner sliding fit
- bearing in slot
- three-point contact on plate

**Shuttle** (contains holder & moves with respect to mount)
- holder fixed between two linear motion system
- holder fixed to side of one linear motion system
- holder fixed underneath one linear motion system

**Arc Motion System**
- swinging arm

Table C-3. Mount Ideas

**Mount to Case** (adhesive, screws, magnets, hook and loop fastener)
- top
- side
- back

**Mount to Bench** (adhesive, screws, clamp)
- arm

**Mount to Wheel** (bearings & stop keep traveler still with respect to case)
- paper ring
- wheel shaft

**Mount to Operator** (allows operator to guide specimen more effectively)
- hand-held user interface
C.3 Holder Concepts

C.3.1 Collet

Figure C-2. Collet Holder Concept

Collets are typically used to hold rounded workpieces firmly during machining operations. The use of a collet in the polishing attachment allows the user to easily grip a hot-mounted specimen or a standard sized cold-mounted. This method is advantageous because the user can examine and mount their specimens for microscope inspection as they have always done. However, the collet has the disadvantage of losing specimen rotational orientation during this process. (Refer to Figure C-2)
C.3.2 Removable Indexed Sheath with Three-Point Grip

Figure C-3. Removable Three-Point Grip Indexed Holder Concept

The use of an adjustable three-point grip allows the specimen holder to fixture different-sized specimens in the same holder. This fixture can be removed from the slide to study the specimen under the microscope. Indexing pins set either in the holder or the slide maintain specimen orientation during this operation. These pins also allow for precise 90° rotation. (Refer to Figure C-3)
C.3.3 Removable Indexed Specimen Holder with Setscrew

![Diagram of removable indexed setscrew holder concept]

**Figure C-4. Removable Indexed Setscrew Holder Concept**

The use of a setscrew in this three-point grip provides a low-cost, reusable fixture that can be indexed to the slide and removed for specimen inspection. Setscrews of different length would be required for the difference in diameter between 1” and 1¼” specimens. The low cost of this concept makes it feasible to use multiple holders with a single polishing system, and the fact that these holders can be reused makes this less expensive in the long run than a disposable holder scheme. (Refer to Figure C-4)
C.4 Traveler Concepts

C.4.1 Sleeve Bearings on Precision Rods

The use of sleeve bearings on rods is a common solution to the problem of smooth linear motion. Because the rods are rotationally ground, obtaining tight tolerances is not an expensive proposition. The structure sketched above is very stable, because the holder is mounted between the rods, and is therefore less susceptible to distortion and misalignment from bending and flexing. (Refer to Figure C-5)
C.4.2 Square-In-Corner Sliding Fit

Figure C-6. Sliding Fit Traveler Concept

This concept is based on the smooth sliding of two flat, low-friction surfaces upon each other. Because this solution uses geometry rather than components, the resulting device is simpler. The spring-ball detents shown in the illustration comprise the most elegant of several possible methods for retaining the carriage in the guide slot without restricting movement. (Refer to Figure C-6)
C.4.3 Stock Linear Motion Components

![Diagram of linear motion components]

**Figure C-7. Linear Bearing Traveler Concept**

Many sources exist for linear motion components, ranging from simple ball-bearing slides to rather exotic rotational and linear bearing assemblies. A simple component like the one sketched above might be the most cost-effective means of providing smooth linear motion. (Refer to Figure C-7)
C.5 Mount Concepts

C.5.1 Rotating Wheel Mount

This concept uses the wheel itself to index the polishing attachment; because of this, the traveler and the holder always run true to the wheel face. In the illustration above, the metal ring that holds the grinding paper to the wheel has been replaced with a rotational bearing. The support structure for the traveler and holder rests on this bearing; this structure is prevented from rotating by a stop arm that rests against the case. (Refer to Figure C-8)

Other possible forms of this concept could use smaller, less expensive bearings than the one shown above.
C.5.2 Removable Case Mount

Figure C-9. Removable Case Mount Concept

The use of the polishing machine case for load bearing and stability solves a number of issues, specifically those related to system life and differing case dimensions. However, this solution does add the complication that the specimen holder must index to the wheel, because there is no guarantee that the case is true to the wheel face.

The pins shown in the sketch above serve as semi-permanent detachable mounts. Other possible forms of this mounting system could use magnets on adhered steel plates, or hook-and-loop fasteners to hold the polishing attachment to the case. (Refer to Figure C-9)
Appendix D: Prototype Manufacturing Specifications

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# Bill of Materials for Polishing Attachment

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Total $335.31
Note: McMaster-Carr P/N 6490K18

Design Group Four

Holder Knob

Material: Polyurethane
Finish: None

SCALE 1:2

Drill and tap 1/4"-28

Φ 2.000

SECTION A-A

Break sharp edge

Φ 1.750

(From ball surface)

.500

1.000

Aprix.

(.353)
Drill 1/4" deep, press fit for 1/8" pin (2x)

SECTION A-A

SCALE 1:2

TBD
### BASIC DIMENSIONAL INFORMATION

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<td>2.7510</td>
<td>2.7520</td>
<td>2.990</td>
<td>3.000</td>
</tr>
</tbody>
</table>

### INSTALLATION INSTRUCTIONS

1. Slip the bearing sleeve into the housing and epoxy into place with Locite™ or similar type bonding agent. CAUTION: Do NOT let any of the adhesive touch the bearing liner. It will harden and interfere with the running clearance.

2. Freeze the bearings at 0°F (-17.7°C) for 30-45 minutes. Using gloves, remove from the freezer and slip the bearings into the housing. As they heat to room temperature, full contact between the bearing and housing will be achieved. The greatest advantage to this technique over traditional pressing is greater accuracy in alignment.

### ORDERING INFORMATION

ORDERING INFORMATION ON PAGES 22-23
Maintenance-free spherical plain bearings, steel/PTFE fabric
(inch dimensions according to ANSI/AFBMA)

Series: GEZ.TE-2RS and GEZ.TA-2RS

\[ d \text{ .75–6 inch} \]

**Type TE-2RS**

**Type TA-2RS**

**Boundary Dimensions**

<table>
<thead>
<tr>
<th>Bore Diameter</th>
<th>Outer Diameter</th>
<th>Inner Ring Width</th>
<th>Outer Ring Width</th>
<th>Angle of Tilt</th>
<th>Frictional Torque</th>
<th>Radial Clearance</th>
<th>Radial Load Ratings</th>
<th>Weight</th>
<th>Part Number</th>
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<tr>
<td>inch</td>
<td>deg.</td>
<td>ft. lb.</td>
<td>inch</td>
<td>pounds (lb)</td>
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<td>1170000</td>
<td>38.59</td>
</tr>
</tbody>
</table>

\( ) Outer ring of bearings with \( d \geq 4 \) inch double fractured.

\( ^{b} \) For further information please consult SKF.
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SCALE 1:2

SECTION A-A

Drill thru and tap for 3/4-20 (4X)
Need 1/2" of usable thread from this surface.

DESIGN GROUP FOUR

Traveler

6061 Aluminum
Anodized

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
FRACTIONS DECIMALS ANGLES
.005
.01
.005

MATERIAL

FINISH

DO NOT SCALE DRAWING

5/8/22

DRAWING NO.

REV.

SHEET

DESIGN GROUP FOUR

REVISION

DATE

CHECKED

APPROVED

RG 3/2/98
Vantage-Downunder™ Latch

A strong, compact undercenter latch
- Choice of stainless or plated steel
- Padlock or secondary catch option
- Adjusts up to 24 mm (.94 in.)
- Exposed or concealed mounting options
- Kickout feature moves unlatched hook from keeper

Latch - Secondary Catch option

Latch - Hasp option

Keepers

Concealed

Exposed
**Panel Preparation**

Exposed base style - Concealed keeper

Concealed base style - Concealed keeper

Exposed base style - exposed keeper

Concealed base style - exposed keeper

**Installation**

1. Use M4 or No. 8 hardware for mounting.
   
   **NOTE:** Maximum head height for mounting hardware on optional hole of concealed base is 2.5 mm (.098 in.).

2. Adjust HOOK to provide desired compression when latched.

3. While securely holding HOOK with pliers, tighten ADJUSTING NUT with wrench.

**Material and Finish**

BASE, HOOK, KEEPER, HANDLE and LINK:

- 1008 Steel, zinc plated plus bright chrome dip or 304 stainless steel, passivated.
- PLAIN KEEPER: 304 Stainless steel, passivated.
- NDT: 1008 Steel, zinc plated plus bright chrome dip or 304 stainless steel, passivated.
- RIVET and PIN: 302 Stainless steel, passivated.
- SECONDARY CATCH: 17-7 PH Stainless steel, passivated.

**KEEPER PART NUMBERS**

<table>
<thead>
<tr>
<th>Style</th>
<th>Finish</th>
<th>LATCH</th>
<th>PART NUMBERS</th>
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<td>94-2338-32</td>
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<tr>
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<td>94-2338-07</td>
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<tr>
<td></td>
<td>Steel, zinc plated</td>
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<td>94-2338-32</td>
</tr>
<tr>
<td>Concealed base with balllock hase</td>
<td>Stainless steel</td>
<td>91-912-07</td>
<td>94-2338-07</td>
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<tr>
<td></td>
<td>Steel, zinc plated</td>
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<td>94-2338-32</td>
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<tr>
<td>Exposed base</td>
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<td></td>
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<tr>
<td>Exposed base with secondary catch</td>
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<td>94-2338-07</td>
</tr>
<tr>
<td></td>
<td>Steel, zinc plated</td>
<td>91-912-02</td>
<td>94-2338-32</td>
</tr>
</tbody>
</table>

**Note:** Black finish available, call for details.

---

Southco, Inc. *Products identified with this symbol are subject to prior sale in the USA, England, Mexico and Australia. For details from a facility nearest you, able to ship from inventory, call 888-478-2000.**
ADJUSTABLE BEARING PLUGS

- Plug material is 316 stainless steel

- Bearing material - "Frelon J" (for stainless steel shafting) is standard. (APN - xx - J)
  Standard "Frelon" is also available for applications to be run on steel.

- Bearing plugs can be purchased separately.

- Ideal for use in many applications as a wear pad.

- Bearing surface area = .300 in²

- MAX Static Load Capacity per Plug = 450 Lbs.

- The use of green Locitite is recommended to hold the adjustable bearing plugs in position.

ORDERING INFORMATION

<table>
<thead>
<tr>
<th>Part No</th>
<th>Description</th>
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<td>APN-16</td>
<td>Optional - Adjustable bearing plug with &quot;Frelon&quot; bearing liner. Use with steel shafting.</td>
</tr>
<tr>
<td>APN-16-E</td>
<td>Standard - Adjustable bearing plug with &quot;Frelon J&quot; bearing liner. Use with 300 series stainless or soft shafting.</td>
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</tbody>
</table>

SQUARE BEARING BENEFITS & FEATURES

- Square bearings run on a single, square shaft eliminating costly components.

- Square bearings maintain radial integrity and can eliminate the need for parallel shafting.

- Can be mounted in any orientation.

- Housings are 6061-T6 aluminum with a standard anodized finish.

- Utilizes standard bearing plugs.

- Bearing plugs are adjustable to maintain tight running clearances.

- Bearing plugs are easily replaced.

- Have all the same characteristics of the standard roundway Simplicity™ bearings:

  - Self-lubricating
  - High load capacity
  - High temperature range (-400°F/ +500°F)
  - Excel in contaminated environments
  - High shock loading abilities
  - Low wear rates
NOTE: 4 Identical Pieces

SECTION A-A
SCALE 2:1
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2X Drilled and Tapped 6-32

6X \(\phi 0.195\)"  

3 1/2"

2 1/4"

2 1/4"

\(\phi 10 1/2\)"

\(\phi 10 1/4\)"

\(\phi 11 3/4\)"

\(\phi 8\)" (Typ.)

SECTION A-A  
SCALE 1:3

Note: Part to be CNC machined from IGES file.
**Latch**

**Latch**

**Keepers**

---

**Latch Body Style**

<table>
<thead>
<tr>
<th>LATCHING SPRING</th>
<th>LENGTH</th>
<th>ASSEMBLY PART NUMBERS</th>
<th>LATCH ONLY (No Keeper)</th>
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</tr>
<tr>
<td>LONG 54.8 (2.16)</td>
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<tr>
<td><strong>STEEL ASSEMBLIES, LIGHT DUTY</strong></td>
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</tbody>
</table>

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- Products identified with this symbol are stocked subject to prior sale in the USA, England, Mexico and Australia. If unavailable from our factory nearest you, allow for shipping time from another facility. Southco, Inc.
Drilled 1/4" deep and tapped 10-32 (3X)

NOTE: 2 Identical Pieces

Bearing Plate

17-4 Stainless Steel
Hardened & Ground

DESIGN GROUP FOUR

SCALE 1:1

SECTION A-A

6.500

.500

4.500

.500

1.000

.313

(.250) TYP.

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NOTE: National Hardware #N117-440
Invention Disclosure
Northeastern University

Appendix E: Patent Application Information
2.2 None of the above are employed by or associated with another institution or company.

3. Description of Invention:

Please see the attached Metallographic Specimen Polishing Attachment Report, prepared for the Northeastern University Mechanical Engineering Capstone Design Course, for complete details on the background, evolution, and design of the invention.

3.1A Purpose of invention:

The preparation of metallographic specimens for microscopic inspection is a common task in materials research. Preparation includes embedding the sample in a polymer base and then polishing the specimen on a polishing wheel. The polishing process uses increasingly finer grits of abrasive paper followed by a diamond paste to achieve an optically flat specimen that can be viewed clearly under very high magnification. This polishing step is labor intensive and generally requires an operator with a great deal of skill. Our invention is an attachment that will mount on many standard polishing machines. It will reduce the skill needed and improve the quality of the polished specimen while allowing the operator to have control over the basic parameters of polishing such as pressure, speed, and time.

(See Sections 1 and 5 of the report for more details and background)

3.1B Description of invention:

The invention consists of three main components: the mount, the traveler, and the holder. The mount is a round rigid plate that attaches to the polishing machine. This plate has a lip so that it sits inside the well of the machine, above the polishing wheel. There are two stainless steel rails and two small elastomer bumpers attached to the plate. These rails allow the traveler to smoothly travel back and forth, while the bumpers prevent over travel.

The traveler includes a vertical linear bearing that will house the holder. This bearing is mounted inside a spherical bearing with a split outer housing. For a specimen to be polished optically flat, the polishing axis has to be held perpendicular to the wheel. This invention uses the spherical bearing to allow for misalignment between the case and the polishing wheel. The two bearings are mounted in an aluminum block that has a clamp which, when closed, keeps the spherical bearing from rotating. This block also has four bearing pads on the bottom that allow it to slide effortlessly on the stainless steel rails.

The holder is used to hold the specimen and is inserted into the linear bearing on the traveler. The holder is equipped with a comfortable knob on the top that also
serves to hold the specimen holder onto the main tube. The specimen holder also has a satellite piece which separates from the holder body and is small enough to fit under a microscope. This feature eliminates the need to remove and replace the specimen itself within the device. Additionally, different size specimens can be accommodated inexpensively by different specimen holder configuration.

The device is simple to setup. The mount is clamped down to the case of the polishing machine with three toggle clamps. Next, the traveler is placed on the rails. With the traveler clamp open, an aligning blank is slipped through the traveler and pressed firmly onto the polishing wheel. This will cause the spherical bearing to swivel to a position that will ensure perpendicularity with the wheel. Once in place, the clamp is closed and the blank is removed. The holder is then inserted into traveler. By sliding the traveler back and forth, the specimen is accurately polished.

3.2 Former approaches and disadvantages:

Polishing metallographic specimens without a device to aid the user often causes the specimen to be faceted, which destroys the usefulness of the specimen when viewed under the microscope. At the very least, it requires a skilled operator to produce consistently non-faceted specimens.

Currently available polishing machine attachments are either automatic or semi-automatic polishing systems that are expensive and complex. These systems are also generally brand specific so that they fit only one type of machine. There are several disadvantages to these systems. Automatic polishing machines are designed to polish several specimens of the same material at once. This is not very practical for a small lab or research group that is only needs to polish a few samples. Additionally, the semi-automatic polishing attachments are expensive, requiring a minimum of $2000 to $6,000.

Other current approaches include simple machines that require the operator to drill a hole in their specimen in order to hold the specimen in the machine. These machines are also expensive. There are also a few patented hand held devices that only provide the user with a handle to hold the specimen but do nothing to ensure that the specimen will be polished properly.

3.3 Features believed to be novel:

The most important feature of this invention is the use of a modified spherical bearing and a clamping device to align to the wheel. This is a simple and rugged method that provides the accuracy that hand polishing lacks. This type of design has not been implemented in any sort of polishing machine attachment that the inventors have found to date. Additional novel features include the shape of the mounting plate; the shape makes it simple to hold the device down with toggle
clamps. The round plate allows the user to rotate the attachment into any orientation that is comfortable for polishing. The sliding mechanism for the traveler is an efficient yet inexpensive mechanism which uses four Teflon-type bearings to move back and forth on the rails. These bearings are well suited for the abrasive environment, take up very little space, and are easy to install. The holder mechanism is novel in that it is easy to use and versatile, in addition to allowing the operator to the ability to index the specimen in ninety-degree increments.

3.4 Advantage of invention over former approaches:

The main advantage of this system over former approaches is the sturdy structure and significantly lower cost. This invention will be very rugged and simple to use compared with expensive electronic-based semi-automatic systems. The material cost of a fully functional prototype was less than $400, and it is expected that the manufacturing cost will be even less. Additionally, this device fits a niche in the market that is not being filled by any other product. Currently, if an automated system is impractical or too expensive, smaller labs are forced to polish samples by hand. This is time consuming, expensive, and produces variable results.

3.5 Alternatives or improvements present or planned:

An alternative attachment that is currently being considered operates on the same principle as the current system, but has the additional feature of a load controlling and measuring device built into the traveler and holder. This device would possibly use a set of cantilever springs and a load cell to adjust the force that is applied to the specimen. This feature would allow the user to maintain a steady, measurable force on the specimen. With a load controlling system in place, the next step would be to add a small electric or pneumatic drive that would allow the specimen to become fully automatic.

3.6 Commercial applications:

Any company or institution that performs any type of metallographic specimen polishing would benefit from this invention. Even if a firm uses an automatic polishing machine, this device could be used to allow them to quickly test new materials without the setup required by automatic machines. The low selling price and the simplicity and versatility of the design makes it a good investment for a wide variety of laboratories.

4. Further research and development which is necessary or desirable before showing the invention to potential licensees:

The invention needs testing to make sure that it will continue to perform as designed. Additionally, a focus group of experienced metallographers will assess
the design and provide feedback that will allow us to address any shortcomings or problems with the invention.

5.1 Names and addresses of potential licensees:

Buehler, Ltd.
41 Waukegan Road
Lake Bluff, IL 60044

Struers, Inc.
810 Sharon Drive
Westlake, OH 44145

LECO Corporation
3000 Lakeview Avenue
St. Joseph, MI 49085

5.2 Companies presently making comparable products:

Buehler, Ltd.
41 Waukegan Road
Lake Bluff, IL 60044

Struers, Inc.
810 Sharon Drive
Westlake, OH 44145

LECO Corporation
3000 Lakeview Avenue
St. Joseph, MI 49085

Allied High Tech Products, Inc.
2376 East Pacifica Place
Rancho Dominguez, CA 90220

South Bay Technology, Inc.
1120 Via Callejon
San Clemente, CA 92673

5.3 Commercial possibilities, indicating estimated market:

Unknown.

6. Public Disclosure or Use
6.1 First publication or public use:

None

6.2 First disclosure to others:

First full written report of background and concept generation was the Capstone Design Class Mid-Term report, submitted to Prof. Achille Messac and Prof. Deanne Harper, both of Northeastern University, on February 9, 1998.

First oral report of this information was presented to the Capstone Design Class on February 12, 1998. The class consisted of approximately 38 students and several members of Northeastern’s faculty.

A second report that contained an unrefined version of the current design was submitted to Prof. Achille Messac and Prof. Deanne Harper on March 9, 1998.

The oral report of this information was presented to the Capstone Design Class on March 11, 1998. Again, the class consisted of approximately 38 students and several members of Northeastern’s faculty.

A third report, attached, will be submitted to Prof. Achille Messac and Prof. Deanne Harper on May 4, 1998. This report contains the information regarding the refined design, prototype construction, and future plans. Additionally it contains all of the previous information.

6.3 First sketch or drawing:

Design has evolved significantly from January 15, 1998 and has been documented in the Group Four Design Notebook, located at 50 Leon St. Room 204, Boston, MA 02115.

6.4 First written description:

The first detailed written description of the invention was submitted as part of the First Quarter Report for the Capstone Design Class on March 9, 1998. The report is archived with Northeastern University Department of Mechanical, Industrial, and Manufacturing Engineering.

6.5 First submission for publication:

None
6.6 Expected publication date for such submission:

None

6.7 Is the invention the subject of any thesis?

No

6.8 Is the invention the subject of any proposal for government or commercial funding?

No

7. Prior related patent applications or patents:

Patent Number 3762103, ‘Machine for grinding and polishing metallographic and mineralogic samples’, issued to Erling-Juul Nielsen of Scan-Dia, October 2, 1973

Patent Number 3930343, ‘Device for mounting specimens’, issued to Detlef Welsch and Horst Washull or VEB Rathenower Optische Werke, January 6, 1976

Patent Number 3931696, ‘Device for making sections for specimens and specimen supports therefore’, issued to Wolfgang Lorenz and Heinz Strubig of VEB Rathenower Optische Werke, January 13, 1976


8. If conceived and/or reduced to practice in connection with a sponsored project, state sponsor, and contract or grant number:

None

9. Contribution of each named inventor:

Prof. Joseph Blucher contributions include helping to define the problem and identify some the key design issues. His insight and experience also helped to solve several of the problems that the team encountered and gave direction in material and manufacturing methods.
The additional inventors, Jonathan Conover, Stuart Dodson, Robert Gordon, David Hesketh, and David Swett all worked as a team; each team member contributed to the ideas generated and the implementation of the design process.

10. Principal contact at Northeastern:

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Signatures of Inventors

_________________________________________________________________________ Date __________

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Witnesses:
Disclosed to and understood by:

_________________________________________________________________________ Date __________

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