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Meso-Machining Of Miniature Space System Components

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This thesis is dedicated to my mother and father for their everlasting love and support they gave me to accomplish this achievement. Their devotion to my education will always be an inspiration to me.

MESO-MACHINING OF MINIATURE SPACE SYSTEM COMPONENTS

by

CARLOS RAMIREZ, BSME

THESIS

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Abstract

Many industries in engineering and science are focusing more on producing mechanisms and system components of magnitudes smaller than existing products. One of the major technologies associated with these demands is the development of meso scale precision manufacturing systems. Meso scale fabrication involves the scaling down of conventional machining to incorporate the use of familiar materials, such as aluminum, steel, and even titanium for machining miniature components. New techniques in meso scale fabrication allow for the machining of miniature space system components in an efficient manner to meet certain specifications. A description of the processes used to accurately machine a complex turbo pump assembly as well as an experimental injector nozzle is given. Specific issues involved with the machining of these scaled down components are also addressed in detail. The surface finish of each pump component is also analyzed to develop methods of improvement.

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Chapter 1: Overview

Ever-changing technology has rapidly increased the demand for much smaller and lighter mechanisms and system components. In recent decades, experiences have revealed the increasing need for millimeter-sized devices in the biomedical, mechanical, and, particularly, the aerospace industry. Micro spacecraft, for example, have become an attractive alternative for space exploration. The reduction in overall size and mass of these space craft is desirable due to the decrease in manufacturing costs, assembly time, and operating costs.

The method typically used in fabricating such small mechanisms is through the use of micro-electromechanical systems (MEMS) technology. This has become an emerging technology that utilizes methods developed for the integrated circuit industry to build microscopic machines on silicon wafers. Layered manufacturing is another recent technology that is used to create components in the millimeter to centimeter range. However, material selection for MEMS technology is very limited to only a few such as silicon and polymers developed through stereolithography. In addition, layered manufacturing methods do not offer the accuracy and material selection needed for certain applications. These materials may prove to be unreliable in high force and high temperature applications such as rotating shafts and actuators.

Advancements in technology have led to the research and development of new methods of manufacturing meso-scaled components and mechanisms that meet many objectives involving size, weight, and cost constraints. The unique development of meso-scale machining lends itself to incorporate conventional machining with MEMS manufacturing. This creates the opportunity to use familiar materials, such as aluminum and stainless steel, with the scaling, high precision aspect of meso-technology to shorten development time and cut costs.

When miniaturizing any device or mechanism, it is very critical to understand the scaling issues involved. The fixturing of parts to be machined, tooling equipment, cutting forces, tolerance control, and surface finish are the primary challenges faced when machining in the meso-scale. This thesis outlines the research and development of manufacturing meso-scale components needed for a high speed turbo pump and micro-thrusters with a high level of accuracy and efficiency.

1.1 PROJECT OBJECTIVES

The objective of this project is to design, fabricate, and test a meso-scale turbo pump and nozzle for miniature thruster applications. The specific purpose of this thesis focuses mainly on the fabrication of a meso scale turbo pump and nozzle. The fabrication of these components combined some of the techniques and materials of conventional machining with the precision and size scaling of meso scale fabrication. The research done for this thesis determines the process necessary to fabricate these components, the accuracy to which they are fabricated, and the surface roughness upon completion of fabrication.

1.2 PRACTICAL RELEVANCE

The development of meso scale fabrication will have applications in the aerospace industry and biomedical industry, as well as other applications. Meso scale fabrication provides an excellent alternative to MEMS technology in that material selection is not limited to mainly silicon or polymers. The scaling down of metal fabrication allows for harder materials to be used where vibrations and temperatures are a factor of performance.

1.3 ORGANIZATION OF THESIS

This thesis is partitioned into six major chapters, which directly describe the work performed. The current chapter presents a brief background on the project and the main focus of this thesis. Chapter 2 provides background information on the methods used to fabricate the turbo pump components and nozzle. Chapter 3 describes the challenges faced while machining, as well as a description of the facilities, equipment, and procedures used for the work performed as described in this thesis. A general description of the tolerance control methods and equipment is given in Chapter 4. Chapter 5 depicts the methods used to improve the surface finish of the meso-scale components. Finally, Chapter 6 contains concluding remarks as well as recommendations for future work.

Chapter 2: Background

New meso-scale technologies are testing the limits of machining to meet objectives regarding size, weight, and cost. Meso-scale machining links conventional methods of machining with those of MEMS technology. All processes used in conventional machining including material removal, surface treatment, and assembly of all components were scaled down throughout the course of this project. The present study is primarily concerned with the scaled down fabrication of turbo pump components as well as an injector nozzle using numerically controlled means.

2.1 CNC BACKGROUND

CNC machining is very useful when machining or fabricating intricate parts and three-dimensional components required by modern technology. CNC stands for computer numerical control and was developed in the late 1940s and early 1950s by John T. Parsons. CNC typically refers to a computer controller that reads G-code commands to drive a tool used to machine components through material removal. Although metalworking mills have been around since the 1800s, Parsons pioneered the automation of the entire process. Parsons used an early IBM computer and punched taped to transfer the G-code to a controller, along with precise servomotor controls. Through this process, he found that he was able to create much more accurate contours than if the process was done manually. The resulting machine was enormous and very expensive.

By the 1960s, a reduction in complexity and price led to increased sales and increased industrial applications. Still utilizing punched tape, the position and sequence of the holes allowed the controller to produce electrical impulses to jog the motors to the necessary position at the appropriate rate. With the advancement of technology, the punched taped used for CNC

metalwork was eventually replaced by various cables and floppy disks. This allowed the computer to read thousands of lines of information to be fed into the CNC machine. This newer technology saved time and allowed for more complex programs to be fed into the controller. The controller also aided in speeding up the machining process. With certain machines and programs, the user must simply enter in a position, tool dimensions, and depth and the controller will automatically determine the correct tool path, speeds, and feed rate. Now, CNC machine controllers can take a CAD model with given material parameters and determine a proper tool path, tool dimensions, speeds and feed rates.

The next generation of CNC machining involves the meso-scale application needed to fulfill many space hardware and biomedical requirements. Meso-scale machining has just recently become prevalent in these industries as well as others. This is partly due to the material selection available for machining as well as the scaled down aspect. As opposed to MEMS technology, meso-scale machining offers the convenience of using familiar materials such as aluminum, steel, and even titanium. This allows for the fabrication of more rigid components to be used in harsh environments. The numerical controlled aspect of meso-scale machining allows for more precise movements of the stepper motors, which permits much smaller cuts.

Chapter 3: Experimental Facilities and Methodology

3.1 MACHINE RIGIDITY

Overall rigidity of the machining environment is a critical factor in producing accurate parts. It is even more so when machining in the meso-scale. This is due to the amplification of vibration relative to the tool diameter. As the tool diameter is reduced, the vibration caused by the machine or other external influences increases. The excess of vibration can cause tool chatter and will dramatically reduce machining accuracy. If the vibration is not corrected, failure such as fractured mills or even part failure can occur. To avoid these problems, the milling machine was centered and leveled according to manufacturer's specifications and placed on a rigid counter top where external vibration was kept to a minimum.

3.1.1 Part Fixturing

Along with stabilizing the machine, part rigidity must also be considered as it usually presents a problem when meso-machining. Many parts and materials that are rigid on the larger scale usually become less rigid when the part size is less than five millimeters in length [8]. This poses problems in the fixturing of the part. If the part is not properly fixtured, it will tend to move during cutting and will dramatically decrease accuracy.

Conventional methods of fixturing parts may not work well in meso-machining. Typically, a part is placed in a clamp vice and then machined. In meso-machining, however, the component being machined is too small and thin to hold in a vice. The holding pressure of a vice may cause the part to flex and thus, decrease the accuracy of machining. In addition, three dimensional parts may not be suitable to hold in a vice because machining is performed on at least two sides of the part. For the parts discussed in this thesis, a clamp vice was not suitable for the parts being machined. The meso-scale turbo pump components were held in place by a four-

jaw lathe chuck fitted onto the rotary head of the mill and a dead center tailstock. This allowed the piece to be rotated 90 deg at a time for the machining of all four sides of the piece as shown in Figures 3.1 and 3.2. Since many of the conventional methods of holding a part do not work on the meso-scale, newer methods of fixturing were used that will not work on larger pieces.

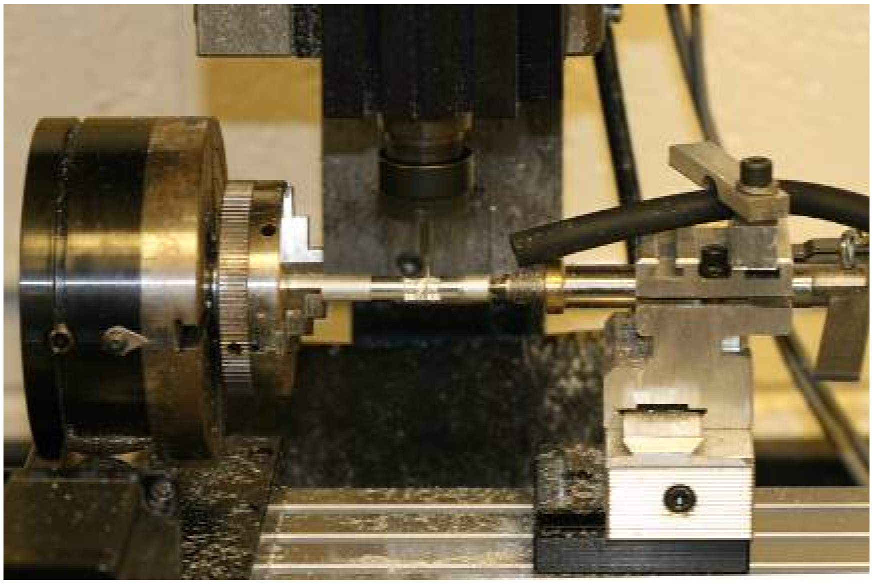

Figure 3.1: Meso-scale component mounted for CNC milling.

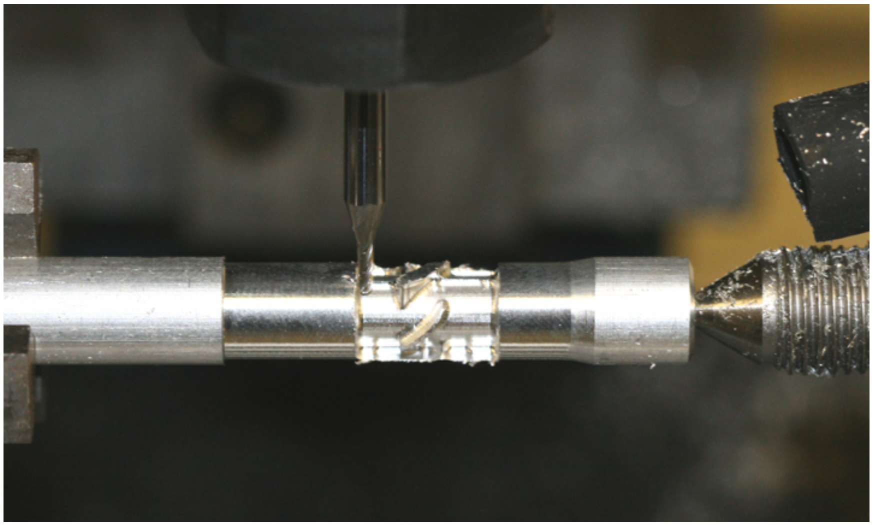

Figure 3.2: Meso-scaled component machined with ball end mill.

During the process of meso-scale machining, the cutting pressures and forces are much lower than in conventional machining [9]. The lower force decreases the tendency of a part to shoot off the milling table or chuck as a result of machining, and a much smaller holding force can be used. Therefore, newer methods of fixturing can be used such as glues, tape, or wax. In most cases, the fixturing method must be destroyed after the part has been manufactured so it the method chosen had to be something expendable [8]. Detaching the part from the fixturing method chosen is also very important. Care must be taken when fixturing small, slender parts using glues or tape because the force needed to pull off the glue or tape may be too much for the part to withstand. Incorrectly pulling the part from the fixture may cause part damage. In this case, wax was used to fixture the pump components for finishing operations. The wax was simply melted away leaving a finished part.

Fixturing a part using candle wax gives rigidity to small parts while providing ease of removal upon completion of machining. The candle wax aided in the machining of components used in a turbo pump and in the nozzle of a micro-thruster. Each component of the turbo pump was designed specifically to mount sealed ball bearings, shown in Figure 3.3, on each end for ease of rotation. These ball bearings are encased in a housing that has an inner bore diameter of approximately 1.17 mm and an outer diameter of 3.97 mm. Since the pump components are three-dimensional parts and have a curved front end, securing them in a clamp vice or even a 3 or 4-jaw chuck cannot be achieved without damaging the part. The candle wax was used to mount and stabilize the part while a recessed area was machined on the inlet guide vane and stator to fit the ball bearings. A round piece of machinable wax served as the mount for the inlet guide vane. A hole was bored out of the center of the wax approximately the same diameter of the part. The part was then placed in the center of the hole and melted wax was dripped into the crevices surrounding it. When cooled, the inlet guide vane remained stable and the machining of

the bearing housing took place. Upon completion of machining, the wax was simply melted off with a flame and the part was cleaned. Eventually, a bismuth alloy was used for its ability to better adhere to an aluminum jig. The aluminum jig was simply a piece of round stock of aluminum with a round pocket bored from the center. The pocket was bored to fit each pump component securely, as shown in Figure 3.4. With each component secured in the jig, the bearing housing was machined. Like the machinable wax, this alloy also has a low melting temperature and is easily expendable.

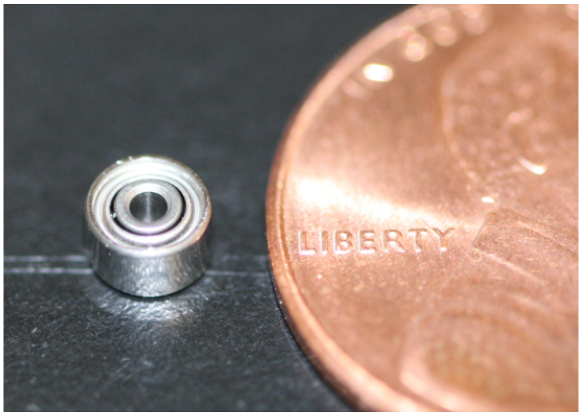

Figure 3.3: Sealed ball bearing size compared to a penny.

Figure 3.4: Pump component placed in a jig with a bismuth alloy.

Candle wax was also used to stabilize the nozzle of the micro-thruster. Upon completion of the inner profile of the conical nozzle, the outer profile was to be machined. The machining of the outer profile involved tapering and linear cutting. When attempting to taper the outer profile of the nozzle, the material became quite thin. This caused the work piece to vibrate at a high frequency and ring like a bell. This can cause poor accuracy when cutting and ultimately, part failure or tool fracture. The excessive vibration was corrected by melting wax and dripping it into the conical nozzle as shown in Figure 3.5. The wax supports the thin wall of the nozzle during fabrication of the outer profile and eliminates the vibration. When the outer profile was complete, the wax was simply melted and removed.

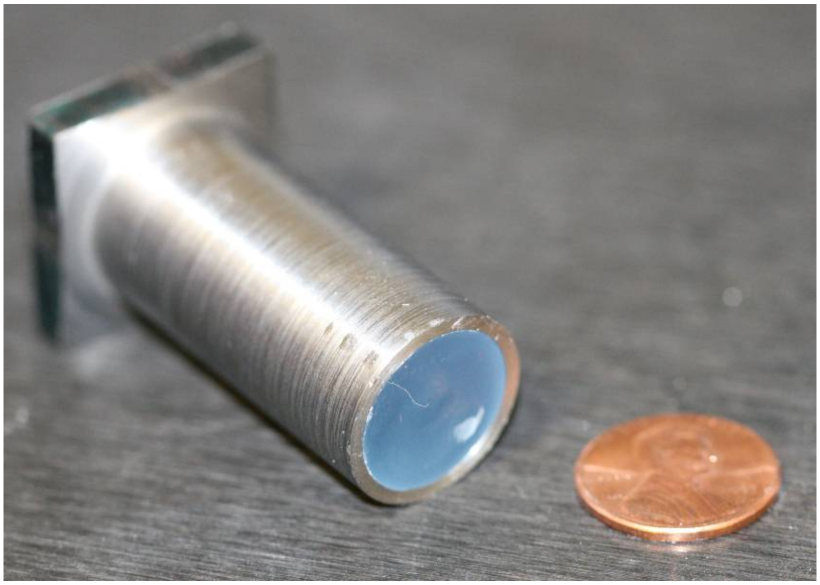

Figure 3.5: Wax used to support the thin nozzle wall.

3.2 EQUIPMENT

In developing high precision meso-scale components, the equipment used during machining becomes very important in that the machines used, defined the tolerances and scale of the component being machined. The selection of equipment was based on the various fundamental functions of conventional milling and turning machines. These functions included

motion controller, spindle speed variation, CNC capability, and precision. In addition, consideration of the component size revealed that a large scale machine and tools would prove inefficient due to lack of tolerance control. In the meso-scale, the combination of motions, motion step size, and forces are orders of magnitude below those of conventional machining. Given the part size, the use of a larger mill and lathe would result in an inefficient utilization of floor space and energy required to operate such large machinery. Thus, tabletop equipment shown in Figure 3.6 was implemented for meso-scale machining.

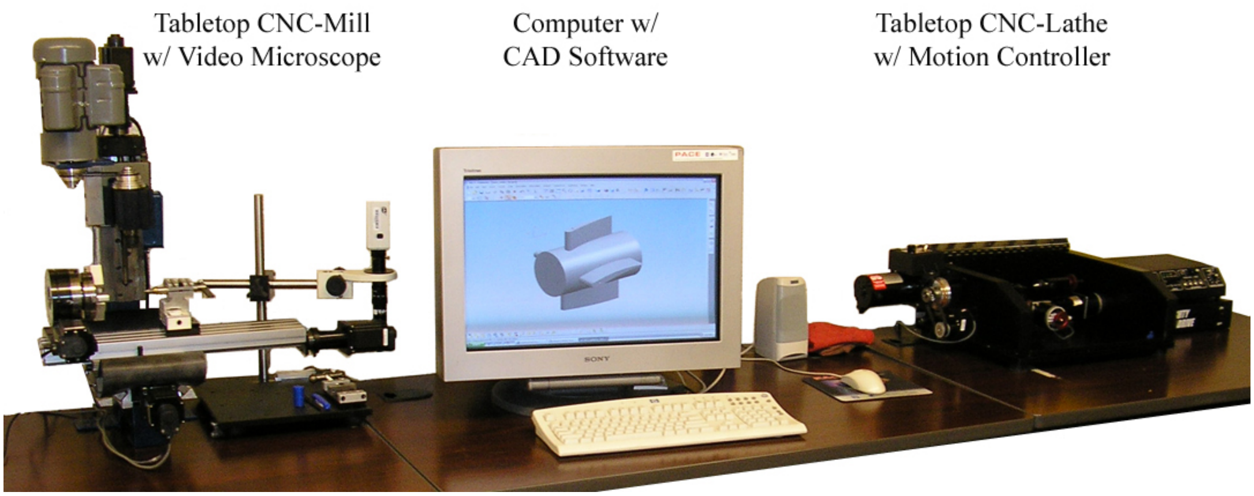

Figure 3.6: Photograph of meso-scale machining equipment.

3.2.1 CNC Mill

One of the methods used in the machining of meso-scale components was through the use of a tabletop CNC milling machine, pictured in Figure 3.7. The tabletop mill proved to be a very valuable piece of machinery in that it was compatible with the UGS NX 4.0 software already obtained by the CPRL. All work performed in making the vanes of the turbo pump, was performed on the mill through CNC programming.

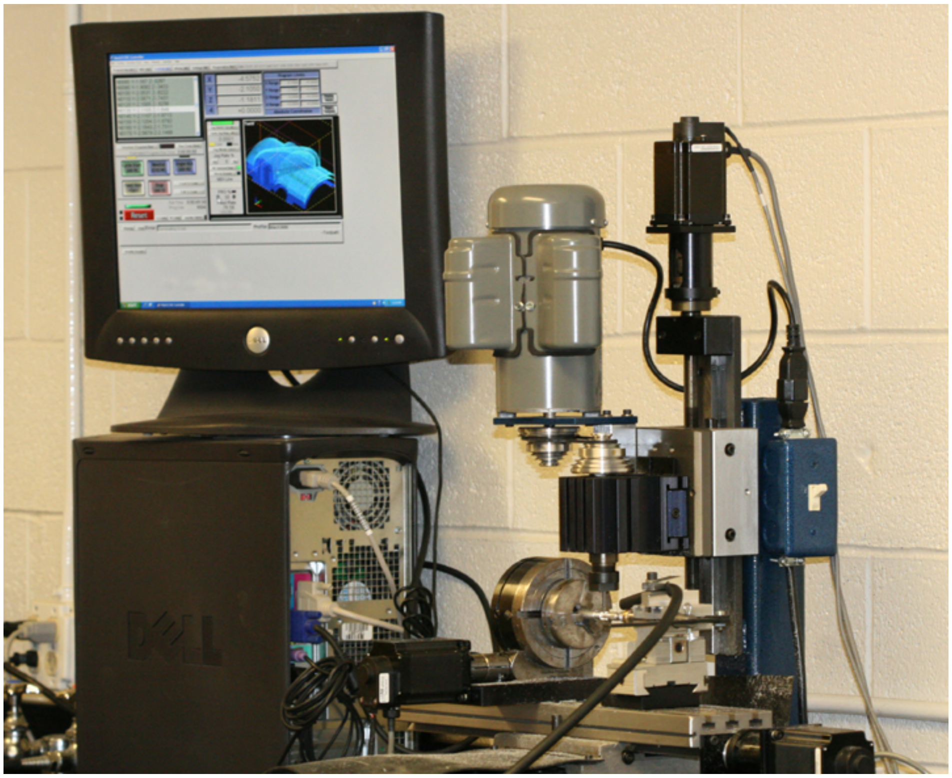

Figure 3.7: Photograph of tabletop CNC mill and computer with software.

The tabletop mill has the capability to produce anything from very simple to very complex geometric forms in wood, plastic, aluminum, and other metals. It utilizes a closed loop stepper motor on each axis to rotate the lead screw to a specified position. The stepper motors used were brushless motors that were controlled precisely through the use of a digital sync lock servo and chopper drivers. This driver limits the current by chopping the drive voltage [2]. The stepper motor and driver combination was a very critical aspect of the milling machine, because of its accuracy and ability to rotate the lead screw precisely.

The tabletop mill was ideal for this type of machining in that the travel in the x, y, and z-axes are 30 cm, 14 cm, and 15 cm, respectively. This allows for the machining of smaller parts that should not be done on a larger machine due to inaccuracies. Using a larger machine also causes an inefficient utilization of resources including space, time, and energy needed to run such a large machine. A rotary axis was also added onto the 3-axis mill to accurately machine

three dimensional parts out of cylindrical or square stock. The rotary axis is a fourth axis that is mounted onto the milling table and has full rotation capabilities to allow three dimensional parts to be cut. The angular resolution of the fourth axis is 0.0125 degrees and has a face diameter of 10.16 cm. The position increment resolution of each linear axis is 0.003175 mm. These small tolerances permit very accurate cuts and precision tooling in meso-scale machining.

The spindle of the milling machine is another key factor of the meso-machining process. As previously mentioned, when machining parts of smaller size many conventional machining methods used on the larger scale are inapplicable. The spindle of the machine must be able to rotate at very high revolutions per minute (RPM) to remove the correct amount of material relative to the tool diameter. The milling machine spindle used is capable of rotating the cutting tool at speeds ranging from 1100 to 11000 RPM. This is done through the use of a ¼ horsepower, 115 V, AC motor. The RPM rating of the motor is 3450 RPM, however, a six step pulley system allows for belt speed variation of up to 11000 RPM. These high spindle speeds allow a higher feed rate of up to 300 inches per minute (ipm) to be used during machining. A high spindle speed coupled with the correct feed rate yield clean, precision machining.

3.2.2 CNC Lathe

Along with the milling machine, a desktop CNC lathe, shown in Figure 3.8, was used in the machining of meso-scale components. The lathe used was a very crucial part in the fabrication of all parts. The CNC mill used was developed to run with its own software and motion controller. The lathe was primarily used for turning blank stock for the turbo pump pieces and exclusively for the nozzle.

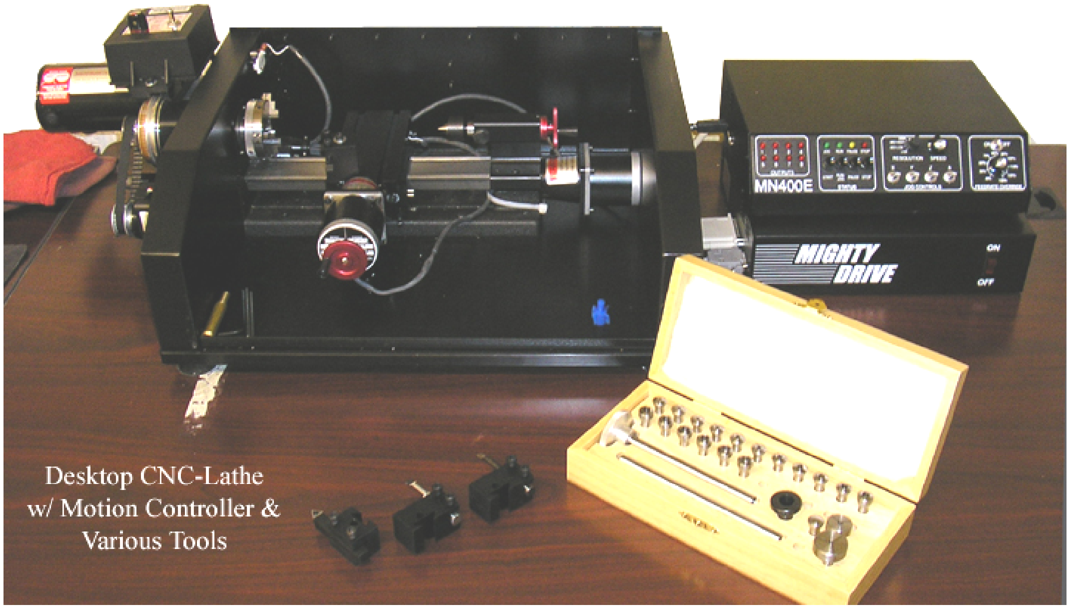

Figure 3.8: Photograph of the tabletop CNC lathe.

The tabletop CNC lathe allowed for the turning of all materials used including wax, aluminum, and mild steel. The distance between centers is 20.32 cm with a cross slide travel of 6.35 cm. Again, this size of machine is ideal for the scale in which the work is performed. Each axis is turned through the use of a lead screw driven by stepper motors. The stepper motors of the lathe have a holding torque of 175 oz-in and a step angle of 1.8 deg. With a step resolution of 0.00254 mm, this lathe permits small cuts and high precision turning. To turn the material, a ½ horsepower DC spindle motor was used. The spindle is capable of speeds ranging from 75 to 2800 RPM.

So as to keep this high accuracy, the vibration of the machine was also taken into account. As with the milling machine, very small vibrations within the lathe are amplified relative to the diameter of the cutting tool. A vibration of 0.00254 mm using a 0.254 mm end mill gives a vibration fraction of 1% of the tool diameter. The same vibration using a 12.7 mm end mill will only give a fraction of 0.02% of the tool diameter [8]. This demonstrates that any

vibration of the machine, tool, or part becomes more and more critical as the tool diameter reduces.

3.2.3 Tool Selection

When machining parts in the meso-scale, many of the conventional machining methods are inapplicable. There are many adjustments that need to be made to account for the smaller sized parts. Spindle speeds and feed rates need to be increased to remove the correct amount of material. With this, end mill and drill bit selection is a key factor for proper machining techniques. For this discussion, the meso-scale machining was typically done using flat end and ball end mills with diameters ranging from 0.794 millimeters to 1.587 millimeters. Several larger end mills were used for other machining, but will not be discussed in this paper. The types used were four flute, single end, regular length end mills. These type of mills offered the small size and durability needed to contour properly according to the pump design.

When machining any type of material with an end mill, coating should also be taken into consideration. Coated end mills provide improved surface characteristics, which increase the life of the mill and improves the surface finish of the part. Many end mills and drill bits have a Titanium Nitride (TiN) or Titanium Carbonitride (TiCN) coating to improve the performance of the cutting tool. This coating reduces friction and improves chip removal, thus, reducing tool temperature. The coating selection of end mills is heavily determined by the material being machined. Since the majority of material machined was aluminum, high speed steel or solid carbide tools were used. Many considerations have to be made when selecting end mills and performance can vary in different materials.

As previously mentioned, spindle speeds and feed rates were taken into consideration for proper machining. High speed cutting techniques are most often used in meso-scale machining. Typically, many high speed cuts are used instead of fewer, slower cuts for maintaining proper

chip load. This is accomplished by adjusting the cut depth, spindle speed, and feed rates. Higher speed cutting techniques coupled with a high spindle speed allowed for a cutting depth of approximately 20% to 40% of the tool diameter [8]. A feed rate of approximately 2000 mm/min was also used during milling. The plunging depth also had to be adjusted due to the tool diameter. Plunging is understood as the initial cut into the material prior to jogging the mill in any direction. The depth of the plunge should be less than 20% of the end mill diameter [8]. For the contouring of the turbo pump components, the depth of plunge did not exceed 0.254 mm. This depth was used to avoid fracturing the end mill while jogging the machine. As aforementioned, maintaining proper chip load is very important as it will help prevent excessive heat and tool fracture. According to manufacturer's specifications Sherline [12], the proper milling chip load ranges from 0.100 to 0.200 mm. As chips of material are cut, they remove heat from the workpiece. Larger chips remove more heat, but too large of a chip may cause the tool to fracture or cause the material to seize to the cutter. On the other hand, too small of a chip load will cause the tool to rub against the material rather than cut the material and raises the temperature of the tool. For these reasons, the proper feed rate was adjusted to the material being cut.

3.3 PUMP COMPONENTS

This section describes the fabrication process of machining a turbo pump to be used in several experiments done by Jonathan Bice and Marcela Cobian of the CPRL. The turbo pump discussed in this section consists of a three part system, intended to rotate at a high rate of speed and impel approximately 50 cubic centimeters per second (cc/s). The design of the entire turbo pump consists of an inlet vane, or flow straightener, a rotor vane to propel the fluid, and a stator vane to straighten out the flow again and act as a diffuser. The turbo pump was designed to be miniature in size, while still maintaining machinability, handling, and operation processes.

The initial step was to design the pump in UGS NX 4.0. This software proved beneficial to this project, as it allowed for the design of the actual pump, as well as aided in the manufacturing of the pump. With the design of the pump components on UGS, the correct milling tool path had to be determined for machining to occur. Careful consideration had to be taken for spindle speed, feed rate, and cut depth. All these factors were crucial in ensuring a correctly dimensioned part, as well as an acceptable surface finish. The manufacturing application of UGS was utilized to simulate the tool path. A screenshot of the CAD model as well as the machining simulation is shown in Figure 3.9. Once satisfied by the simulated end product, the necessary code was generated to run the tabletop CNC milling machine.

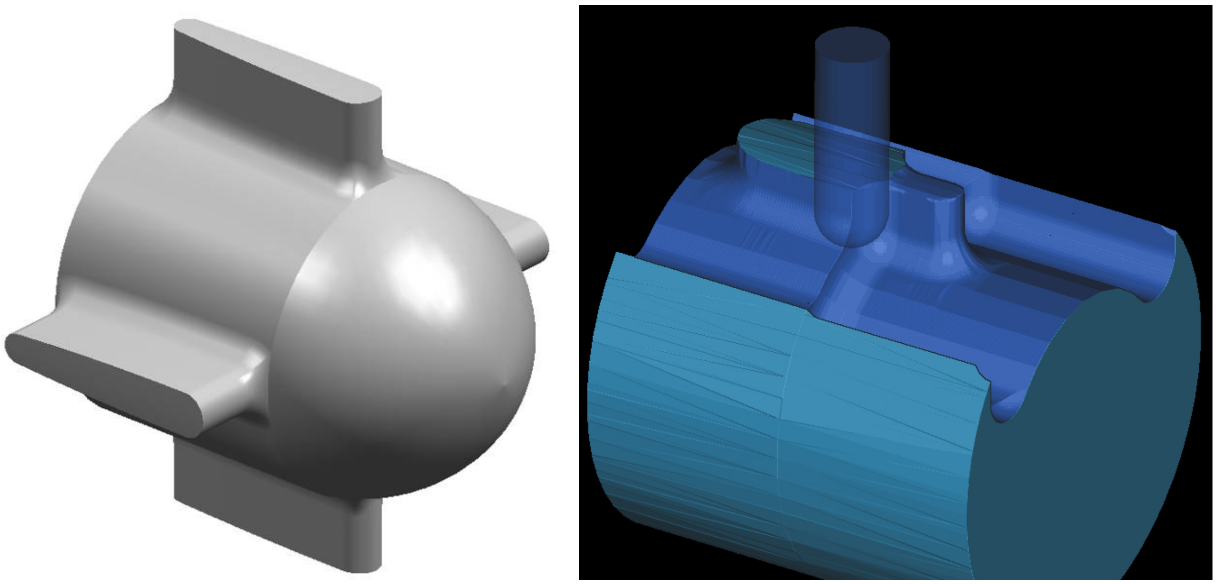

Figure 3.9: Computer model and simulation of tool path.

Prior to machining each vane, a blank had to made and setup in the machine. In this case, a blank is a piece of round stock with dimensions matching those of the simulation, used to machine the finished product from. A piece of aluminum round stock was turned down in the lathe to specific dimensions and center drilled on both ends for use of a live center tail stock. This ensures the rigidity of the piece being machined with little or no deflection from the cutting

forces, yielding a more accurate cut. Upon completion of the blank, the stock was then setup on the mill using a rotary table and a dead center tail stock. Each axis was zeroed out utilizing a Starrett edge finder and a video microscope. The mill was stepped approximately 0.00254 mm at a time to obtain an exact zero on a given axis. These tools allowed precision alignment of the x, y, and z axes. With the blank stock in place, and each axis aligned, the G-code created in UGS NX 4.0 was input into the Mach3 CNC software and the proper feed rate and spindle speed were adjusted before start up. A feed rate of approximately 25 mm/min was set for the initial plunge of the 1.19 mm ball end mill to avoid fracture of the mill. A spindle speed of 6500 RPM was set to remove the correct amount of material. As the program continued, the feed rate was set to approximately 75 mm/min. The piece being machined was divided into three different passes, each with a different cut depth from the initial z-axis zero. Each pass plunged the mill 0.5 mm, which removed the correct amount of material without mill fracture. Compressed air was used to cool the first two passes and non-chlorinated brake parts cleaner was used to cool the finishing pass. The brake cleaner helped to cool the piece and aided in removing swarf from the flutes of the ball end mill. The use of the brake parts cleaner also improved the surface finish of the pump component during the CNC machining process over the use of compressed air. Upon completion of the first side of the component, the rotary table was turned 90 deg and the second side was machined using the same procedures. The third and fourth sides were also machined using these procedures. The inlet vane and stator were both designed with a smooth-converging nose and tail end, respectively, that allowed for conditioning the flow. These ends were the final CNC operations performed on the pump components. As seen in Figure 3.10, tool marks were created from machining the nose of the inlet vane. To remedy this problem, the part was placed in the lathe and fine grit abrasive paper was used to smooth the surface.

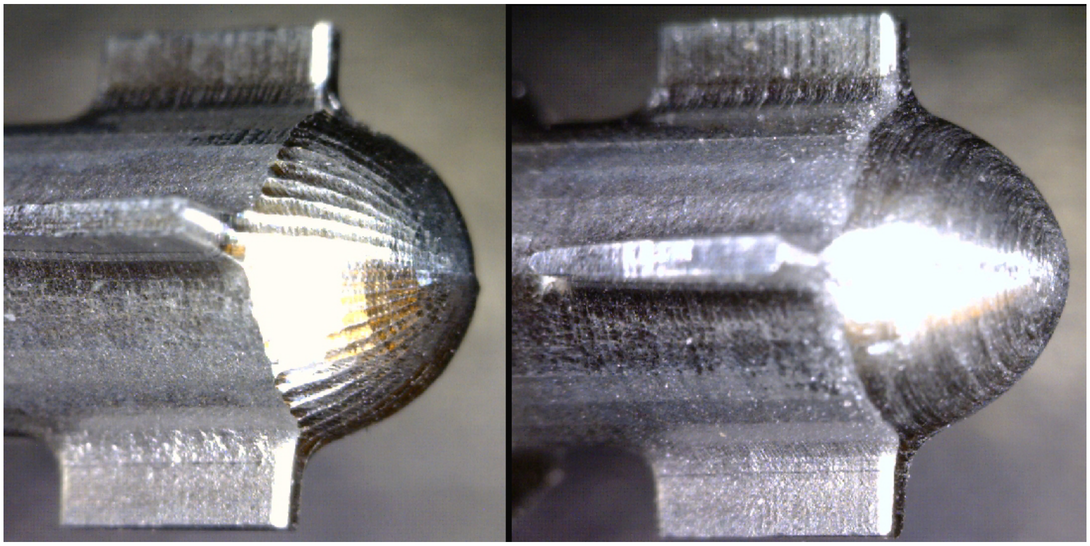

Figure 3.10: Photograph before and after using abrasive paper on inlet vane nose.

Upon completion of the CNC portion, each pump component was separated from the stock piece using the parting tool on the tabletop lathe. As previously mentioned, a jig was created using aluminum stock, in which a hole was bored out of one end and used to hold each pump component in place for machining. With the piece in the jig, the hole was filled with a bismuth alloy to hold the component in place. The bearing housing was machined using the mill and the rotary table, in which the mill was offset from center and the rotary table was rotated 360 deg. until the specified diameter was met. The mill was plunged approximately 0.10 mm per step until the specified depth was achieved. Once the bearing housing was milled, the bismuth alloy was simply melted and the pump component was easily removed from the jig. The ball bearings were then placed in the housing as shown in Figure 3.11. Figures 3.12 and 3.13 show the final pump assembly.

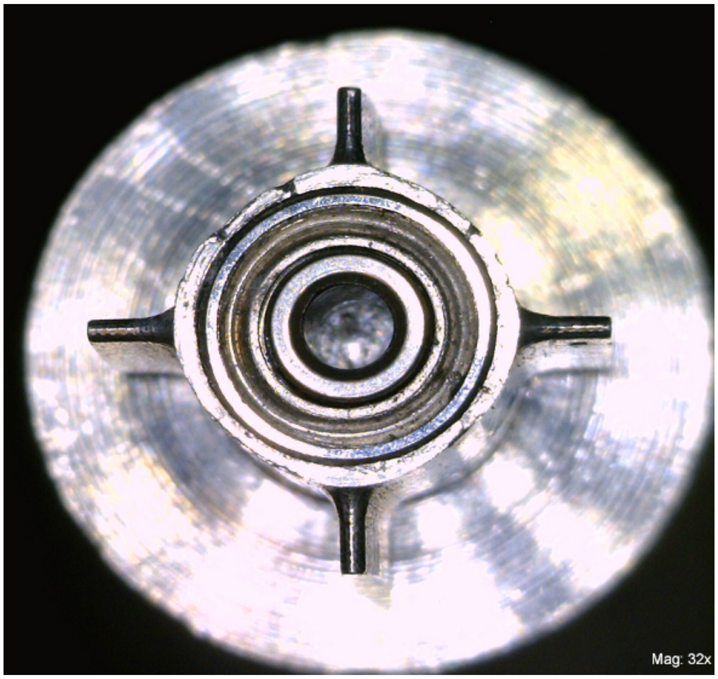

Figure 3.11: Photograph of bearings placed within inlet guide vane.

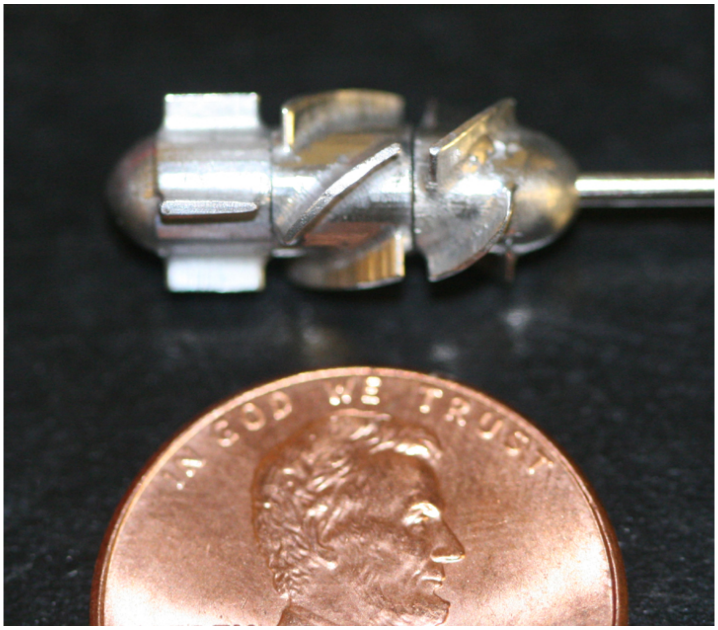

Figure 3.12: Photograph of turbo pump assembly.

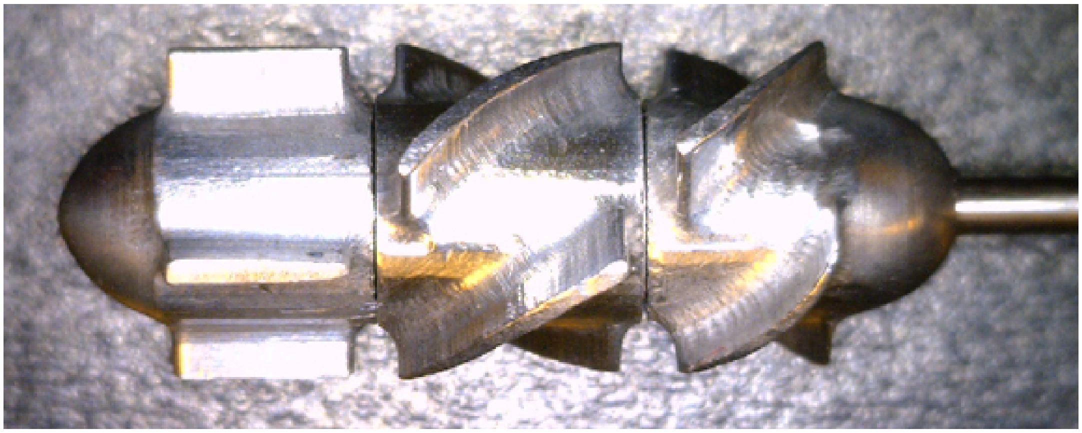

Figure 3.13: Photograph of turbo pump assembly.

3.4 INJECTOR NOZZLE

This section describes the design and fabrication of a converging-diverging nozzle to be used with an experimental injector previously used in research conducted by Phillips [10]. The design of the converging-diverging nozzle consists of a combustion chamber, throat, and nozzle. The intent of the fabrication was to produce a converging-diverging nozzle that was capable of producing approximately five Newtons of thrust. The nozzle was also designed with a large expansion ratio, while still maintaining a machinable throat diameter. Other factors such as size and weight were also heavily considered in producing this nozzle.

The nozzle is intended to operate in a vacuum under choked flow conditions. The converging-diverging nozzle was then designed using UGS NX 4.0 to meet these conditions. The nozzle prototype was first fabricated of machinable wax to verify the order in which the machining processes must be done. This model was not to be used for any type of testing for strength and durability purposes. Upon completion of the wax prototype, a 6061 T6 aluminum nozzle was machined as the second prototype. An aluminum nozzle was machined to provide an opportunity to test without the combustion aspect of a nozzle. Tests were performed to investigate flow characteristics on the nozzle using carbon dioxide and helium. These experiments set the benchmarks for the nozzle design. Figure 3.14 shows a CAD model of the

converging diverging nozzle compared to a finished aluminum nozzle. The third nozzle designed was machined out of 1018 steel for its high melting temperature. The steel nozzle was intended to be fired using hydrogen and oxygen at atmospheric pressure and room temperature. The throat diameter of the nozzle was decreased by approximately 50% from the design of the aluminum nozzle to the steel nozzle.

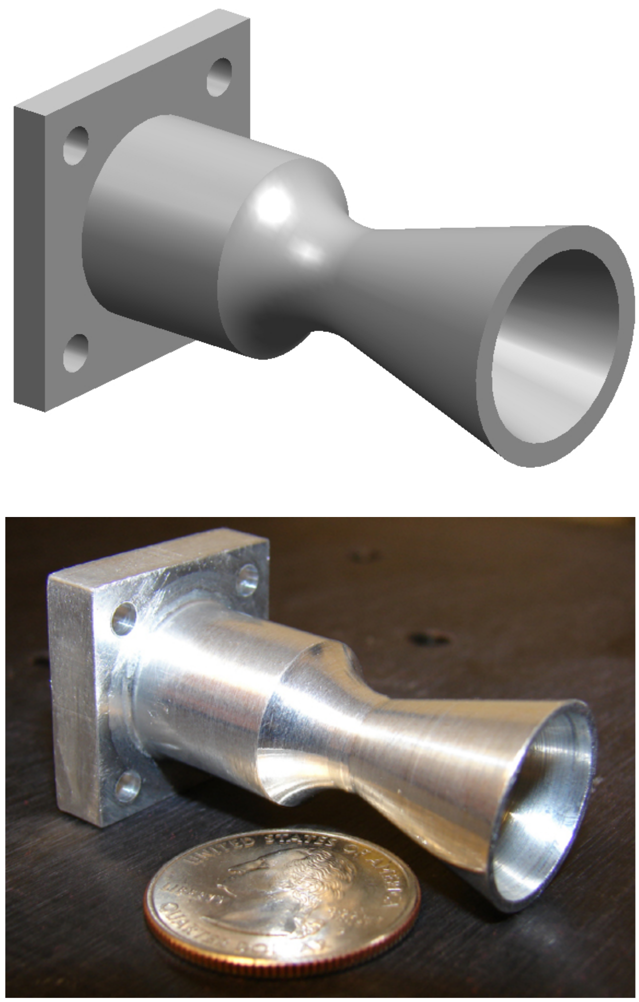

Figure 3.14: CAD model and machined aluminum converging-diverging nozzle.

The following section will cover the process used in fabricating the converging-diverging nozzle. The fabrication of the nozzle required the use of the aforementioned desktop CNC lathe. A piece of square stock aluminum was cut to an approximate length a little longer on both ends than necessary. The piece was then chucked into the lathe and trued on both ends to the correct

length using a solid carbide cutting tool. The remaining piece was then turned down to the dimension of the exit diameter of the nozzle with a flange left on the chucked end of the piece. This flange is necessary to mount the nozzle to the experimental injector for testing. Next, a center drill was used to drill both ends of the work piece. This ensured that the piece was trued for proper turning and accuracy. A hole was drilled through the center of the entire work piece. This hole had the same dimension as the throat of the nozzle. The diverging section of the nozzle was next to be machined. For the machining process of the diverging section, a series of increasingly larger drill bits were used to create a stepped cone, as shown in Figure 3.15. The sizes of the drill bits ranged from the throat diameter, to the exit diameter in increments of 0.4 mm. The drill depth of each bit was critical in maintaining the proper half angle and profile of the nozzle. Drilling too deep or not deep enough would result in a potential inconsistency in the inner profile of the nozzle, which could cause faulty test data. So as to insure the correct drill depth is achieved, an excel spreadsheet, developed by Nakka [9], was used to determine the correct depth given a certain cone half angle, throat diameter, and exit diameter. The spreadsheet calculates the drill depth of each drill bit with a cut allowance of 0.01 inches. This spreadsheet had to be slightly modified to include the 50% reduction in throat diameter. After drilling the throat diameter, the drill diameters were progressively increased as the depths decreased, yielding a stepped cone patter.

Figure 3.15: Stepped cone pattern of the diverging nozzle .

Once the stepped cone profile is achieved, a conical burr, shown below, of the same cone dimensions was used to remove the "steps" from the wall of the nozzle. A layer of candle wax was dripped onto the surface of the burr before inserting it into the nozzle. The wax helped in reducing the amount of chatter, or noise, produced from the vibration of deburring the nozzle. Small, progressive cuts were taken with the burr to avoid too much swarf build up on the burr.

Figure 3.16: Conical, double cut burr used to remove "steps" in the nozzle.

With the diverging section of the nozzle complete, the next step was to machine the converging section or the combustion chamber. The converging section was machined by chucking the diverging section and drilling the combustion chamber to a predetermined depth. The combustion chamber was simply drilled with a ½ inch, 118 deg. drill bit. This left a converging half angle of approximately 31 deg.

The next machining operation performed was the machining of the outer profile of the diverging section of the nozzle. Prior to machining the outside of the nozzle, the entire converging-diverging nozzle was filled with candle wax, shown in Figure 3.17. This eliminates most of the chatter, caused from machining, that could result in poor cutting and a poor finish.

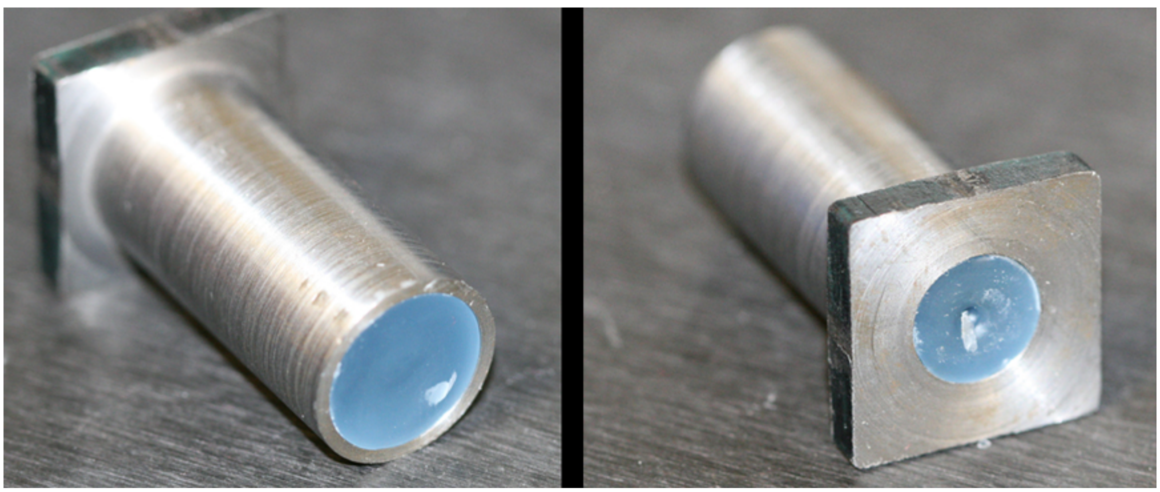

Figure 3.17: Converging diverging nozzle filled with wax to eliminate tool chatter.

Typically, a compound slide would be used to cut the taper of the nozzle profile. A compound slide is a device used to cut angles or tapers that cannot be cut by swinging the headstock of the lathe. It is mounted onto the lathe cross slide and adjusted to the correct angle of cut. Then light cuts are taken on the material to achieve the specified taper. Normally, this type of tool would be ideal for this situation. However, the CNC lathe was equipped with a program generator that allowed the user to create a G-code program to cut tapers. The program allows the user to input initial and final diameters, taper angle, and depth per cut. Since the

nozzle was machined of aluminum, a cut depth of approximately 0.005" was taken during each pass. The tool used was a left hand cutting tool. This ensured a clean cut without a large amount of heat generated from the cutting tool. When the steel nozzle was machined, a smaller cut depth was used as well as a slower spindle speed and feed rate.

The combustion chamber outer profile was the next operation performed. The combustion chamber was simply turned down to the designed outer diameter. This simple operation was done by manually turning down the combustion chamber up to the mounting flange. Upon completion, the throat curve was the next operation. The outer profile of the throat was designed with a curve that smoothly transitions the combustion chamber to the nozzle. This serves the purpose of removing a large piece of aluminum to both reduce mass and improve heat transfer. As with the nozzle outer profile, the throat curve, shown below, was turned utilizing the CNC capabilities of the supplied software. This operation was done by cutting a quarter circle curve using light cuts, until the specified radius was achieved.

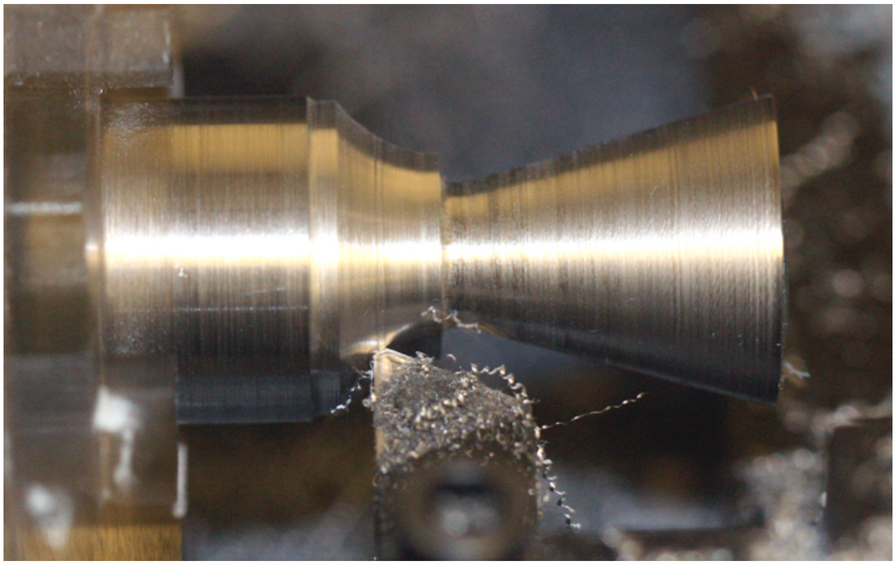

Figure 3.18: Nozzle throat curve machined on the CNC lathe.

Once the throat curve was complete, the four mounting holes were drilled on each corner of the mounting flange. The final step in machining the nozzle involves finishing the nozzle using emery paper to polish the flow surface, round the throat entrance, and remove any burrs. Rounding the throat entrance is a very important operation, in that the efficiency of the nozzle is impacted by the flow of the combustion products. The process used involved using emery cord of a thickness slightly smaller than the throat diameter. Figures 3.19 through 3.21 show the final converging-diverging nozzle made of steel.

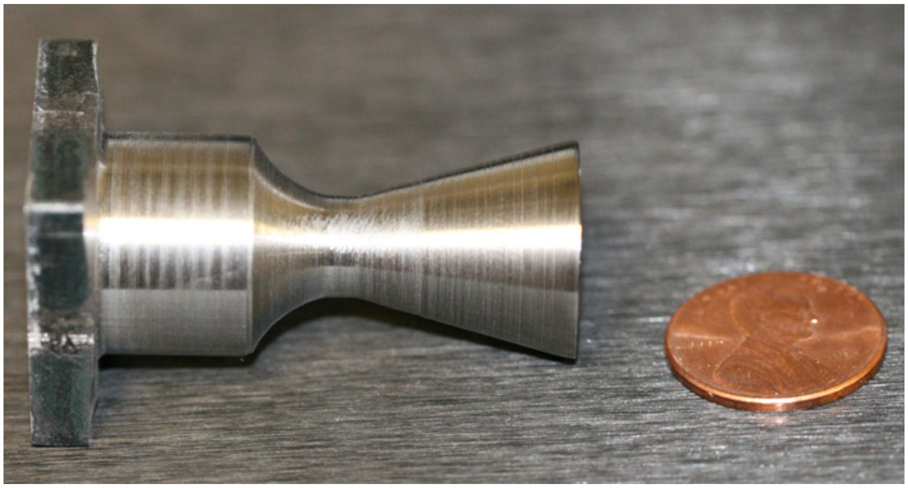

Figure 3.19: Side profile of final converging-diverging nozzle.

Figure 3.20: Nozzle inner profile.

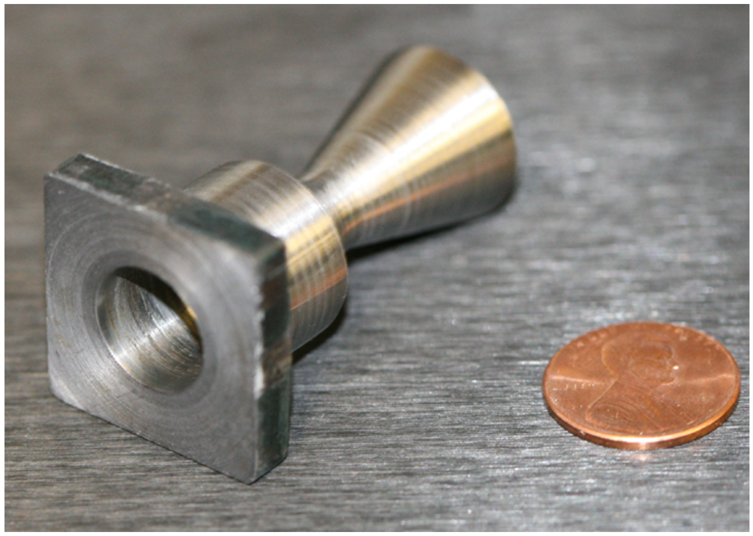

Figure 3.21: Converging-diverging nozzle.

Chapter 4: Tolerance Control

In any type of machining or fabrication, dimensional accuracy of the work done is a very important issue that must be addressed. The typical precision required in the macro scale is in the order of a few hundred microns. In the meso scale, this accuracy becomes even more significant due to the overall size of the part being machined. Thus, the precision requirement is higher and comparable to wafer stepper accuracy [14]. Relative accuracy is defined as the ratio of attainable tolerance to work piece size. An objective of this study is to develop objects with a relative accuracy between 10^{-2} and 10^{-4} when machining objects between 0.05 mm to 5.0 mm [15]. This level of accuracy can be achieved by utilizing precision machines as well as precision measuring devices to ensure precision.

4.1 MEASURING DEVICES

The tools used in accuracy verification were a vital part in every aspect of this project. Various measuring tools in conjunction with digital imaging devices were used to confirm a high level of accuracy as well as aid in miniature tool positioning. Typically, tools such as a digital caliper, a video microscope, and a digital microscope were used for such purposes.

4.1.1 Digital Caliper

A digital caliper is perhaps one of the most commonly used measuring devices in most conventional machine shops. The caliper is a device used to measure the distance between symmetrically opposing sides. The caliper used in this project is a Cen-Tech, six inch digital caliper. It allows a measurement accuracy of 0.0254 mm with a resolution of 0.0127 mm. This caliper is capable of displaying metric or SAE dimensions, which can be toggled by a push of a button. The zero setting was checked periodically due to close tolerance measuring.

4.1.2 Video Microscope

In addition to a digital caliper, a video microscope was used for tool positioning as well as the inspection of machined components. The microscope used was a JAI CV-S3200N and features a resolution of 768 x 494 pixels. The microscope was connected to a television monitor through a BNC to RCA cable connection, in Figure 4.1. The use of the monitor permitted real time video of the item placed under the microscope. This was especially effective in finding the zero setting of the z-axis of the mill. The majority of the machining of the pump components was done using a 1.194 mm four flute, ball end mill. Since the flutes on this ball end mill are very small, it can prove very difficult with the naked eye to visually inspect for chips forming when the spindle is rotated manually. Without a z depth gauge, the microscope connected to a television monitor provided a high enough zoom to step the z-axis 0.00254 mm at a time and enable the inspection of chip formation when the spindle was rotated. When a very light cut was taken by the mill and tiny chips formed as a result, the zero setting of the z-axis was achieved. This setting was very important for the machining operations performed. If the z-axis was offset even by a small amount, the plunge of the mill would not be correct and the dimensions of the part would be inaccurate.

The video microscope was also used to inspect the parts upon completion of machining. The surface finish and geometry of the part was the primary focus of using the microscope for inspection. If the surface finish was not suitable, further work was performed to correct any flaws in the finish. The geometry of the part in question was also inspected for inconsistencies such as burrs or misaligned holes. Further operations were also performed if the geometry of the part was not correct.

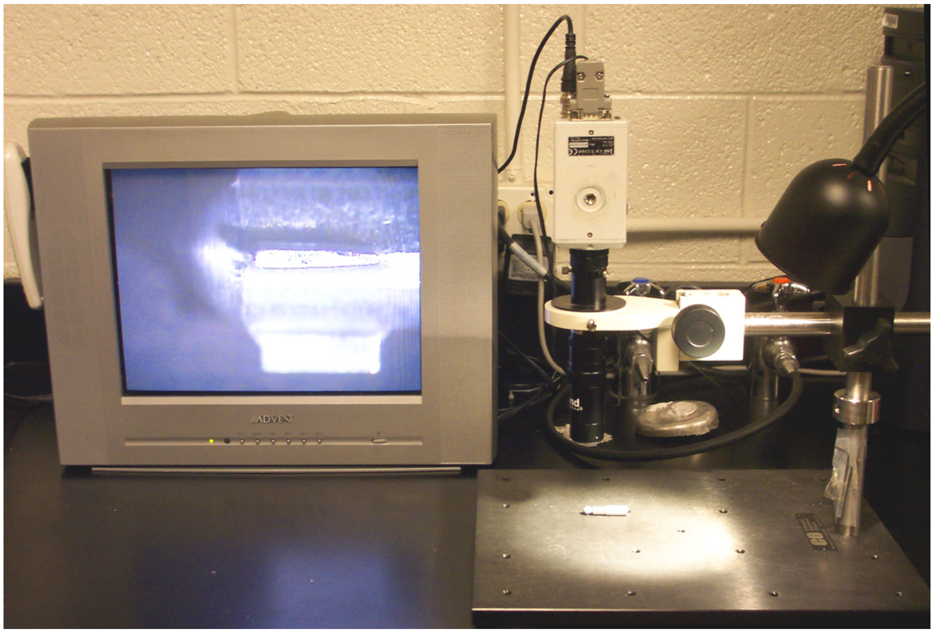

Figure 4.1: Image displayed on television monitor as viewed through video microscope.

4.1.3 Digital Microscope

The digital microscope is a very similar tool to the aforementioned video microscope. It is essentially a microscope with an LED light source connected to a computer. The computer displays the projected image of the microscope as well as runs the software needed to acquire an image, as shown in Figure 4.2. The microscope used is a Dino-Lite Digital Microscope model AM413T. This model features a resolution of 1024 x 1280 pixels and a magnification of 0x to 50x and 200x. This model is also capable of rendering video with a frame rate of up to 30 frames per second (fps). The software included with the microscope allows the user to capture an image and take measurements of the specimen right on the screen. This feature was very useful in that the part can be taken directly from fabrication to the microscope to check the accuracy of machine and ensure that the dimensions are within tolerances.

Figure 4.2: Image projected onto computer as viewed through digital microscope.

4.2 PUMP COMPONENTS

The pump components were all machined using the CNC tabletop milling machine. This machine has a step resolution of 0.003175 mm and a mechanical repeatability of 0.0127 mm. The mechanical repeatability is considered how close a system returns to a desired location time after time under repeated cycling. Considering the step resolution and repeatability, the tolerance for each pump component was established at ±0.05 mm. Upon completion of the pump components, each part was individually inspected first using the digital caliper for ease of measurement. Using the digital caliper, the dimensional deviations measured can be summarized in Table 4.1.

Table 4.1: Summary of pump component dimensional deviations

Pump Component	Total Width (mm)	Total Length (mm)	Vane Length (mm)
Inlet a	-0.06	-0.08	-0.05
Inlet b	+0.08	+0.03	-0.01
Inlet c	-0.07	+0.05	-0.06
Rotor a	±0.00	+0.18	N/A
Rotor b	-0.02	+0.05	N/A
Stator a	±0.00	-0.11	-0.01

4.3 INJECTOR NOZZLE

The injector nozzle was primarily machined using the CNC tabletop lathe. This machine has a step resolution of 0.00254 mm. However, most of the significant machining operations, such as machining of the throat, the converging section, and diverging sections were done manually. These operations were all done carefully using a drill bit index and the tailstock spindle, which is accurate to 0.0254 mm. The depths of each drilling operation were calculated by using the excel spreadsheet developed by Nakka [9]. This ensured that the proper pattern was maintained for the specified cone angle. The proper cone angle and height designed was achieved through the use of the conical burr previously mentioned, which has a cone angle of 15.5 deg and a length of cut of 25.4 mm. The proper throat diameter was achieved by using a 1 mm drill bit and emery cord to remove any burrs and sharp edges left by the conical burr.

Chapter 5: Surface Finish

The surface finish of the pump and micro thruster components machined is critical in their respective performance. Any type of burr or discontinuity in the material may also yield faulty results under experimentation. In the macro scale a surface blemish on a part may not be very critical in its performance. In the meso scale, however, given the overall size of the pump components and nozzle, any type of surface blemish will have dimensions comparable to those of the actual part. To remedy this potential problem, several methods of surface treatments were considered and tested. The first was a method of electroplating, which proved to be a valuable method in that the process leaves a smooth finish to be tested. Another method considered was electropolishing the material. Both methods have their respective advantages and disadvantages yet, still provide an excellent surface finish.

5.1 ELECTROPLATING

Electroplating the material after all machining was complete was considered to improve the surface finish of the part. Electroplating is the process of using electric current to coat an electrically conductive material with a thin layer of metal. The primary application of this process is improving the surface finish of the material to desired specifications. The electroplating process uses a plating solution to electrically coat the part with a certain metal. An anode and a cathode are connected to a power supply which is usually a battery or rectifier. When the power supply is switched on, the metal and the anode is oxidized from the zero valence state to form cations with a positive charge. The cations associate with the anions of the solution and are reduced at the cathode to deposit onto the metallic material. The plating material is usually a single metal, not an alloy. The result of electroplating is a smooth, even surface finish.

A major drawback of electroplating is that the dimensions of the part change as a result of adding more material. When certain dimensional specifications need to be met, the final dimension must compensate for the amount of plating added on. This is done by adjusting several factors such as amperage, temperature, and time of submersion. Another drawback of electroplating is the possibility of the plating chipping off. This may be due to the excessive use of the part and general wear and tear. This may cause faulty data under testing due to surface blemishes.

The electroplating process can be used for future work to improve the surface finish of the turbo pump components.

5.2 ELECTROPOLISHING

Another proposed solution to the surface treatment was the method of electropolishing. This method is the opposite of electroplating in that rather than adding material onto the part, material is etched off to remove any burrs or cutting grooves from the surface. Sometimes called reverse plating, electropolishing is an electrochemical process which polishes a metal by etching the work piece. This process uses an acidic viscous medium to transport the ions to allow discontinuities on the surface to become planar. For the electropolishing process, the work piece is placed in a temperature controlled bath of electrolyte solution and connected to the positive terminal of a power supply. The negative terminal is attached to the cathode and also placed in the electrolytic solution. The cathode attracts the particles removed from the anode when electric current is applied. Similar to electroplating, the amount of material removed depends on many factors including amperage, temperature, time, and the distance the work piece is from the cathode [3]. For the electropolishing process, several tests were run to see which produced the best finish. The specimens used were 9.56 mm diameter round stock aluminum that had been cut to approximately 6.35 mm. All tests were done using a three to one ratio of methanol to nitric

acid. The temperature of the solution, time of submersion and amperage were the variables of interest. The temperature of the solution ranged from -62.00 °C to 48.88 °C. The time ranged from 3 minutes to 10 minutes. The results indicate that keeping the methanol-nitric acid solution at a higher temperature and submerging the part for a short period of time removed the most material. This produced a smooth, polished finish.

Table 5.1: Electropolishing results aluminum round stock.

Sample	Time In	Time Out	Temp. (°C)	Voltage	Amps	Initial Diam. (mm)	Final Diam. (mm)	Initial Mass (g)	Final Mass (g)
1	2:57 pm	3:07 pm	20.39	10	.25	9.56	9.55	1.21	1.21
2	3:48 pm	4:08 pm	-62.0	10	2.2	9.56	9.54	1.21	1.20
3	4:57 pm	5:02 pm	46.6	10	3.6	9.55	9.46	1.27	1.23
4	11:30 am	11:33 am	44.44	10	2.6	9.56	9.49	1.30	1.27
5	11:43 am	11:46 am	48.88	6.5	2.0	9.55	9.48	1.08	1.04

These results were used to determine how much metal is removed during the electropolishing process using a methanol-nitric acid bath. The results of these samples can be used for future work to electropolish the turbo pump components without etching away the vane tips.

Chapter 6: Conclusion and Recommendations

With today's leaps and bounds of technological advances, fabrication of smaller mechanical components is highly desired. Meso scale machining offers the convenience of using familiar materials, while maintaining dimensions on the miniature scale. This type of machining was conducted through the design, machining, and assembly of turbo pump components as well as a converging-diverging nozzle.

6.1 CONCLUDING REMARKS

The machining of such small components created many challenges throughout the entire process. Some of the main challenges included machine rigidity as well as part rigidity, maintaining tolerance control, and improving surface finish. New methods of part fixturing were evaluated and implemented to overcome deflection and vibration during machining. Precision stepper motors on both the mill and lathe combined with high resolution imaging devices helped ensure that all dimensions were within tolerance. To improve the surface finish of the pump components, new methods of machining and polishing were introduced. This was coupled with different tools to obtain an improved finish on all parts.

The UGS NX 4.0 software combined with each CNC machine was essential in machining such intricate parts. The software aided in the design of each component into a three-dimensional solid model as well as simulating the machining tool path of each component. Time was saved during this process because if the simulation revealed any discrepancies or flaws, the model could be easily modified as needed and machining would continue. There wouldn't be any lost time due to errors in machining. Each CNC machine also had its own software which made the transition from solid model to the final G-code very simple. As a result, machining of each component was done in a timely fashion compared to outsourcing each component.

6.2 RECOMMENDATIONS

The intent of this project was to investigate the capabilities and limitations of scaling down conventional machining to produce space system components. Much research is being conducted to explore smaller scales and different materials. Further work that should be performed to optimize the meso scale machining process may be as follows:

- Investigate the cutting forces and pressures produced during machining with commonly used cutting tools on various materials. This would yield a better understanding as to how small a part can be produced by scaling down conventional machining.
- Modify the machining process of the converging-diverging nozzle to include the machining of titanium.
- Improve the surface finish of the turbo pump components by continuing the study of the electroplating and electropolishing processes.

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Curriculum Vita

Carlos Ramirez was born in El Paso, TX on August 5, 1983, and is the middle child of Francisco and Maria Isela Ramirez. He was raised in El Paso where he graduated from Bel Air High School in May 2001. Upon completion of high school, he enrolled in the Mechanical Engineering Bachelor's program at The University of Texas at El Paso. While attending UTEP, he earned two summer internships with General Motors in Warren, MI and Mesa, AZ before completing his Bachelor's Degree in May 2006. Immediately following the completion of an undergraduate degree, Carlos began work on a Master's Degree during the summer semester of 2006. He will conclude his graduate degree in the fall semester of 2007.

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