Developement of an Encapsulation Process for use in a Universal Automated Fixturing System

by

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ABSTRACT

The perfect fixturing system would immobilize the work piece so as to allow one to cut as aggressively as the machine tool would allow. It would never obstruct the cutting path or the cutting tool. It would locate the workpiece with absolute accuracy. It would support the work piece entirely. It would easily allow for complete automation of its functions. With such a system, the line that divides rapid prototyping and mass production could be erased and manufacturing one piece would be as cost and time efficient as manufacturing ten thousand.

The development of a universal automated fixturing system is a step towards creating such a perfect fixturing system and is expected to have a profound effect on machining. Such a fixturing system will allow the decoupling of design from manufacturing, and essentially bring product design and development one step closer to true concurrent engineering. Universal Automated fixturing can also transform a machine tool into a rapid prototyping machine with many advantages over current rapid prototyping methods. The entire design process can be sped up, allowing companies to be more responsive to market changes.

Research aimed towards creating a universal automated fixturing system is discussed in this dissertation. We focus on developing an entirely new manufacturing process, which we call encapsulation molding, essential for making automate universal fixturing possible. Furthermore, we describe the hurdles of implementing such a system and the science which has been applied to better understand the process. Lastly, this dissertation contains a proposal for further work that must be pursued to truly create a universal automate fixturing system.

Thesis Supervisor: Sanjay Sarma

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Chapter 1: Introduction

The functions of fixturing are to locate, immobilize and support a workpiece while being machined. The objective is to minimize the geometrical errors between the actual product of the manufacturing process and the intended conceptual product. Often referred to as workholding, fixturing is a fundamental subsystem of a machine tool and of manufacturing in general. The goal of this research is to develop a system that will automate the functions of fixturing for any given geometry, i.e. to develop a universal automated fixturing system for a machine tool. The benefits of such a system will be far ranging, with applications in rapid prototyping and mass production environments.

1.1 Fixturing and Its Role in Design and Manufacturing

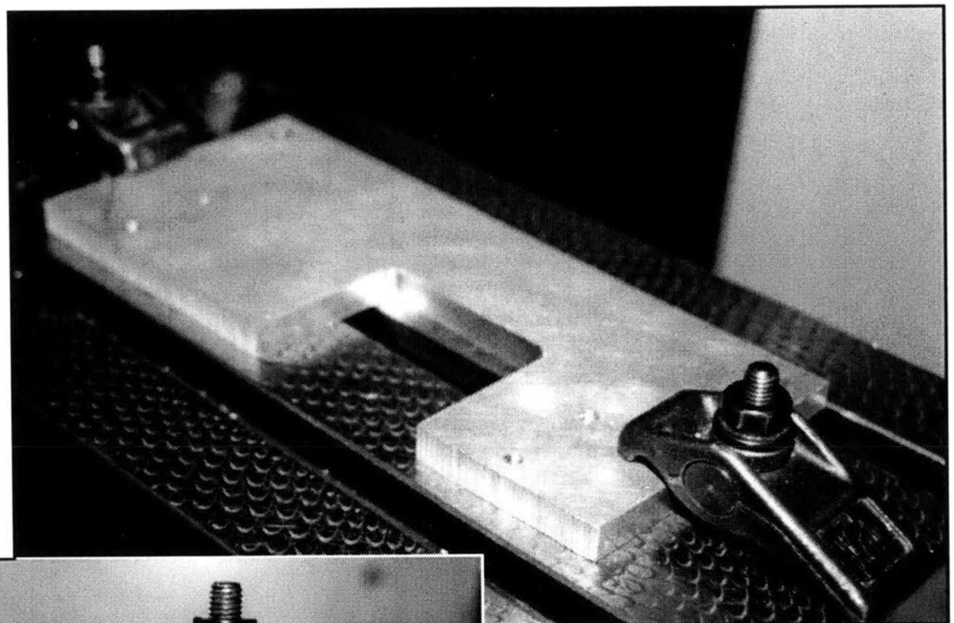
Because fixturing has such a simple function, fixturing issues have often been overlooked during the design of products and during the design of the manufacturing systems used to create those products. It is usually an afterthought that haunts designers and plant managers alike. Most do not realize that fixturing is the interface between design and manufacturing, between the part and the manufacturing environment. Without careful planning, the fixturing system will conflict with the manufacturing process and the manufactured product.

Designers cannot complete a design without understanding how the part can be manufactured. Often, additional elements must be added to the design to aid in its manufacturing. Features such as location surfaces and mounting holes, which may not be necessary for the functions of the part, are vital for its production. On the manufacturing side, the generation of toolpaths, the cutting parameters and the setup sequences are strongly coupled to fixturing decisions. These issues can not be resolved until the fixturing system is determined. Thus, the general approach to design and production becomes iterative. Information and decisions about the product are transferred back and forth between designers and manufacturers, each requiring different, and many times, conflicting functions for the product. Such iterations delay the product's time to market, increases its costs, and almost always effects its quality.

Fixturing does not have to be the wall that divides the two sides, but instead, one that connects the two together. Imagine, if one were able to devise a workholding process that could properly fixture any geometry that designers and manufacturers would wish to create. That perfect fixturing system could immobilize the workpiece to allow one to cut as aggressively as the machine tool would allow. It would never obstruct the cutting path or interfere with the cutting tool. It would be able to locate the workpiece with absolute accuracy. It would be able to support the workpiece entirely, damping out any vibrations excited by the machine tool. Such a fixturing system would allow designers and manufacturers to work concurrently, unhindered by what the other will or might do.

1.2 Past Fixturing Technology

The most generic fixturing devices used in machine tools are the two-walled vise and the toe clamp. Mechanically straight-forward, they use a screw mechanism to transmit



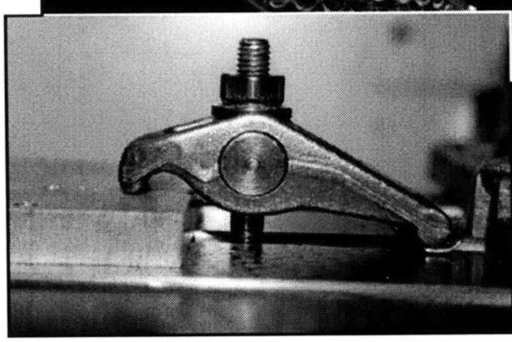


photo taken by Elmer Lee

Figure 1.1 Photograph of toe clamps used to fixture flat object on a machine bed

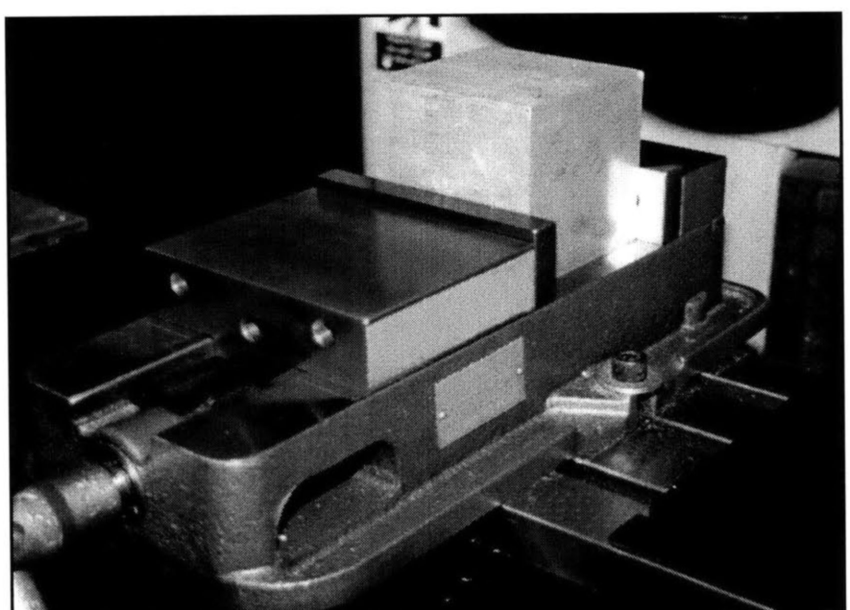


photo taken by Elmer Lee

Figure 1.2 Photograph of a 2-walled vise clamp, used mainly for the workholding of rectangular, fairly stout parts

frictional holding forces to the workpiece. They are inexpensive and convenient for fixturing average rectangular parts. Likewise, the setup times and accuracy of these devices are reasonable.

However, as manufacturing and machining have become more aggressive, the inadequacies of these simple vises and toe-clamps have become apparent. They can not meet the higher accuracy requirements, accommodate the more demanding part geometries, nor satisfy the decreasing setup times demanded by today's standards. Implementing complex automated processes using such devices becomes tedious and time consuming. They can not maintain the repeatability for processes that requires multiples setups. The required clamping forces are often too great and localized, resulting in part deformation, yielding, and warping.

They are equally limited in their adaptability. Two-walled vises can only accept rectangular shapes and toe-clamps, flat plate stock. Adapters, such as V-blocks, could be bought or built, from "soft jaws,"[1] to interface other geometries, but each new setup requires new adapters, increasing manufacturing costs and time.

1.3 Current State of the Art

The development of new fixturing technology has focused mainly on decreasing setup time on the machine tool and increasing fixture modularity. It has been a slow evolution grounded in old methods. Current state of the art fixturing available in industry can be view as extensions and improvements on vises and clamps.

1. Soft jaws are usually aluminum plates. The footprint of the intended workpiece can be machine into these plates to allow clamping forces to be spread more evenly over the workpiece.

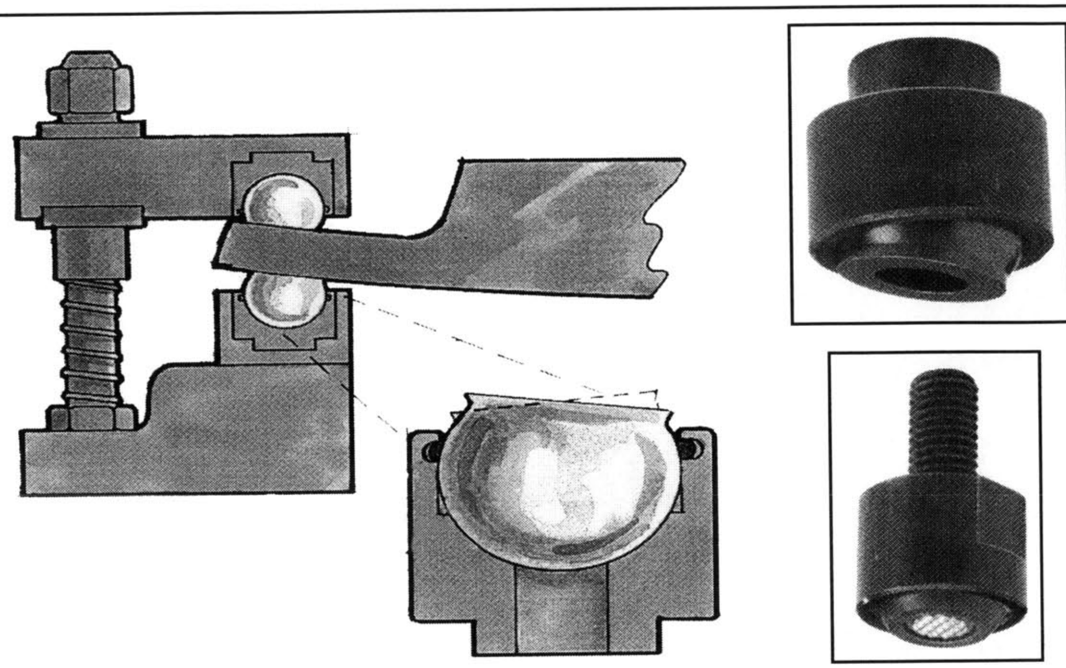


Figure 1.3 Illustrations of self-aligning ball pads for workholding of rounded plates

Photos courtesy of Advanced Machine & Engineering Co.

For example, as shown in Figure 1.3, to deal with rounded plates, toe clamps have been adapted by placing a ball and socket mechanism at the tip. This fixturing device has evolved to fill in gaps where a conventional toe-clamp has proved to be ineffective. Extremely effective and well designed to handle curved plates, its use, unfortunately, is only limited to plate stock. To tackle other fixturing problems, new fixturing elements are needed. Much of the development of new fixturing technology has moved in the same evolutionary manner. Each product has a specific niche. Fixture elements are designed for a specific operation or a limited class of operations. Combining specialized fixtures has lead to modular fixturing, the assembly of these small components into an arrangement able to handle fixturing needs each could not, separately.

By using stronger and harder materials and more accurate manufacturing processes, fixturing devices have been designed to provide better accuracy. The use of precision ground pins, such as those shown in Figure 1.4, to align to plates with precision bored locating holes has increased repeatability in situations where multiple setups are required. Their walls are mounted on flexures to allow its diameter to increase by a couple thousands of an inch without shifting the pin's center. This allows the pin to fit exactly into a bore, without any sloop

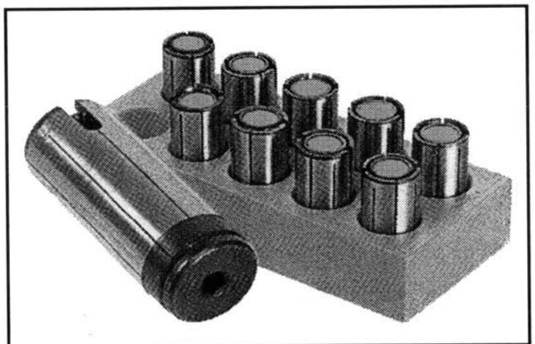


Photo courtesy of System 3R Inc.

Figure 1.4 Photograph of precision ground expansion pins.

Shown in Figure 1.5 and Figure 1.6, by increasing the size and scale of these fixturing elements, parts are place in large batches so that setup time is distributed over the entire batch quantity. And with the development of accurate pallet changes, which allows an operator to load a new batch of part into one fixturing element while another is being machined, and then swap the two, down time on the machine tool has decreased dramatically.

However, thus far, no fixturing product or technique has been able to offer completely universal workholding solution that is easily automated. Modern fixturing systems have not only left the current divide between design and manufacturing unresolved, they have also created an addition division, that between mass production and prototyping. Pallet changing and batch style fixturing methods have proved to be very economical in mass

Photo courtesy of TRIAG Inc.

Figure 1.5 Photograph of a tombstone fixture setup

Photo courtesy of TRIAG Inc.

Figure 1.6 Photograph of a cluster of two walled vises

production situations. However, in situations where only a few parts are needed, the cost for tooling increases dramatically, becoming a large percentage of the total part cost. In these cases, using pallet changers and batch fixturing processing becomes economically inviable. Modular tooling has been used successfully to accommodate parts that are to be machined in small batches. Unfortunately, the required planning and setup time is still quite extensive, leaving plenty of room for improvement.

1.4 Universal Automated Fixturing

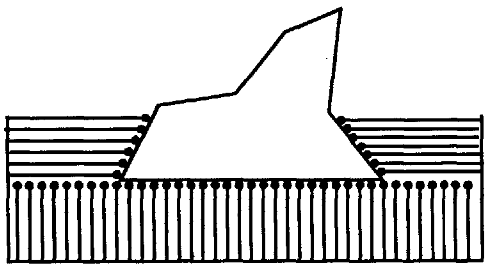
Many researchers have attempted to build universal fixturing systems, fixturing systems that would allow one to fixture any part regardless of its geometry. The approaches to developing such a system, though they vary quite extensively in their detailed designs and physical implementation, can be generally categorize into three different methods. The first is the use of finite number of fingers or pins to conform and support the arbitrary geometry. The second is the use of a fluidized bed, where the workpiece is submerged in a bath of a finite number of micro-spheres which can conform to the arbitrary geometry. By applying pressure to the top surface of the bath, a holding force will be applied to the workpiece through contacting microspheres. The last method is to use a phase-changing material which, in the liquid state, will conform to the arbitrary geometry and when solidified, will trap the part inside and maintain holding forces on it.

Each of these three methods, shown in Figure 1.7 , have their disadvantages. The finger approach is fairly difficult to implement. The long slender fingers are prone to buckling which make the stability of the entire fixturing system questionable. The lack of damping is also another reason why this method has had little success. The fluidized bed

Categories of Universal Work holding Techniques

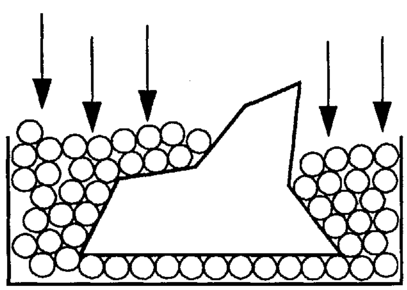
Disadvantages

Bed of Fingers



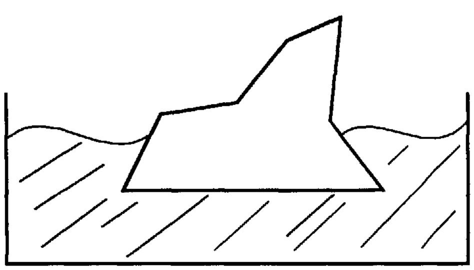
Fingers are unstable
Provides little damping
Interferes with toolpaths
Mechanically complicated

Fluidized Bed



Instability due to voids
Can not interfere with toolpaths
Requires additional external forces

Phase Change Encapsulation



Hardware intensive
Complex Process

Figure 1.7 Illustration of the different techniques for implementing a universal fixturing system

also has stability issues which are highly dependent on the size of the microspheres. Perfect packing is impossible to achieve. Thus, voids and inclusions inside the bed can allow the part to shift. The maximum holding force of fluidized beds is relatively small. Thus, most applications of fluidized bed fixturing has been in assembly, where fixturing is generally less demanding. In addition, both of these methods create access problems for the cutting tool. The toolpath cannot intersect the fixturing system without damaging itself or the fixturing system. On the other hand, the use of phase change material to encapsulate a workpiece allows one to escape the problems faced by the other two. The stability of the fixturing system depends on the yield strength and Young's modulus of the encapsulator. Cutting into the encapsulator will not likely damage the work tool or the fixturing system since the encapsulator is usually much softer than the workpiece or the cutting tool. In addition, because phase change fixturing results in greater surface area contact between the part and the fixturing elements, one can be sure that it will offer superior damping. However, the need for heating systems, a delivery system of the liquid encapsulator, and a variety of other support devices, will tend to increase costs and complicate the design of such a fixturing system.

All three methods still face the challenge of locating the part or positioning the part accurately if features already exist within the workpiece. Without modification, none of these three different methods provide a means to creating a reliable universal automated fixturing system.

1.5 Motivation Behind Developing a Universal Automated Fixturing

Imagine if one were able to transform a milling machine into a manufacturing vending machine. One simply has to provide a CAD file of the desired part, upload it into the manufacturing environment and then simply walk away. A couple hours later, the milling machine has generated the correct toolpaths, checked for errors and gouges, designed the fixturing system, selected the right stock size, and machined the part completely. As simple as putting a few quarters into the drink machine and waiting for a bottle of soda to come out, this machine deliver prototype parts quickly and economically. Rapid prototyping could be done using the intended material. Designers could not only "get a feeling" for the appearance of their designs, but they could also test its functionality and performance. Development of a product would take weeks, not months or years.

However, at this time, automation of conventional fixturing is possible only on a part by part basis. Special "hard" tooling must be designed and manufactured that automate part handling, positioning, and workholding. Consequently, for short runs, such as in prototyping and one of a kind products, specialized fixturing accounts for a large percentage of engineering time and machining costs. Lead times are long, and fixed cost, high.

Creating an automated universal fixturing system is one of the steps in creating a better rapid prototyping system. Alone, such a fixturing system could allow an operator to manually create complex one-off parts. Alone, it can save the operator time and effort, and reduce operator errors. Combined with sophisticated CAM software being developed at the Rapid Autonomous Machining Laboratory at MIT, and with robotic material handling systems, one can turn a milling machine into a rapid prototyping machine. The automated

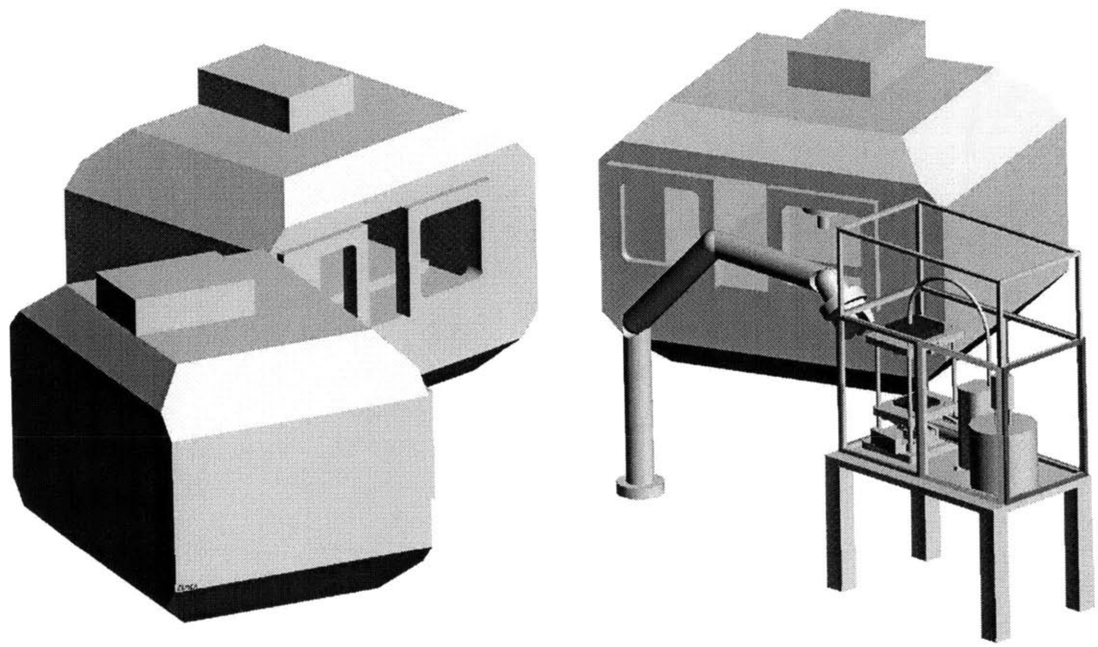


Figure 1.8 Illustration of the general model of the envisioned rapid prototyping center:
A cluster of three milling machines surround the universal automated fixturing system. A robotic arm transports the workpiece back and forth between the milling machines and the encapsulation fixturing system.

universal fixturing system that is being proposed, discussed in the coming chapters, will allow one to fixture and machine two completely different parts in the same setup, using the same machine tool. In essence, with this fixturing system, one will be able to apply mass production techniques and optimization to prototyping situations. A fixturing system that allows one to transform unique, arbitrary parts into one generic norm, gives one the freedom to machine all those parts as if they were the same, transforming a cluster of machine tools, meant to run one-off parts, into a machining cell. Such a system, shown in Figure 1.8, would revolutionize the way engineers and designers think about product development and manufacturing. Just as the concepts of mass production--assembly lines, interchangeable parts--have revolutionize manufacturing, so shall rapid prototyping through machine tools. The ability to create one part as quickly, efficiently, and as economically as creating a thousand of those parts, that is the next frontier in manufacturing and product development.

Chapter 2: The Encapsulation Process and its Application Towards Fixturing

In designing the universal fixturing system, it has been decided to develop the system using phase change fixturing techniques. Although extremely design intensive, it has, by far, the most potential to succeed. As mentioned in the previous section, the use of a phase changing encapsulation process has many disadvantages and hurdles to overcome. Professor Sanjay Sarma describes many of these problems and possible solutions in his doctoral work at the University of California, at Berkeley.

One of the fundamental challenges in using phase change encapsulation is that of locating and aligning a workpiece with pre-existing features. The common practice has been to use locating dies for which the features of the part are aligned to matching features specially machined into the die. Unfortunately, the use of the locating die essentially corrupts the system's ability to become automated and universal. For each new part, a unique die must be designed and manufactured. Thus, our approach will steer way from the usage of locating dies and to, instead, develop a process plan which will allow us to locate the part by some other means. Again, the research Professor Sanjay Sarma performed as part of his doctoral work at Berkeley in 1995, under Professor Paul Wright, which this research is built upon, had followed the same goal.

2.1 Basic Process Steps of Encapsulation

The process we have formulated, in its most abstract form, can be described as follows. A piece of stock, rough cut to the approximate dimensions of the finished product, is encapsulated in a lower melting temperature material, molded into a perfect rectangular block[Sarma 95]. This block is then placed inside the machining environment so that a machining procedure or part of one can be performed on the block. Being a block form, the fixturing within the machine tool is completely automatable. The machining procedure is usually, but not always, limited to one side of the block. The block is removed once the first machining procedure is finished and the features that have been machined into the block are covered with the lower melting material in order to restore the block to its original rectangular block shape. Once remolding is complete, the block is placed into the machining center again so that additional features can be placed on the present or another side of the block. These the machining and refilling, are repeated until all features have been machined into the block. After such time, the block is taken out of the machine tool, and its temperature raised to a temperature above the melting point of the encapsulator but lower than that of the original stock. After the entire volume of the encapsulator has been liquefied and has flowed off, the finished piece can be easily extracted [Sarma 95].

This process plan is a modification of the classical encapsulation technique described in chapter 1. We can avoid using locating dies by prohibiting features to exist in the workpiece before encapsulation. Instead, the locational datums are taken from the precision molded walls of the encapsulation cube. All features machined into the block after the encapsulation is referenced from those walls. (Consequently, one important constraint of the re-encapsulation and restoration procedure is that it may not disturb the wall locations.) This modified encapsulation process also allows one to completely machine all and any features on a part from one of the six directions of access. Fixturing of a part can be easily automated. Each setup is identical to the ones previous to it. There is no need for specialized hard tooling.

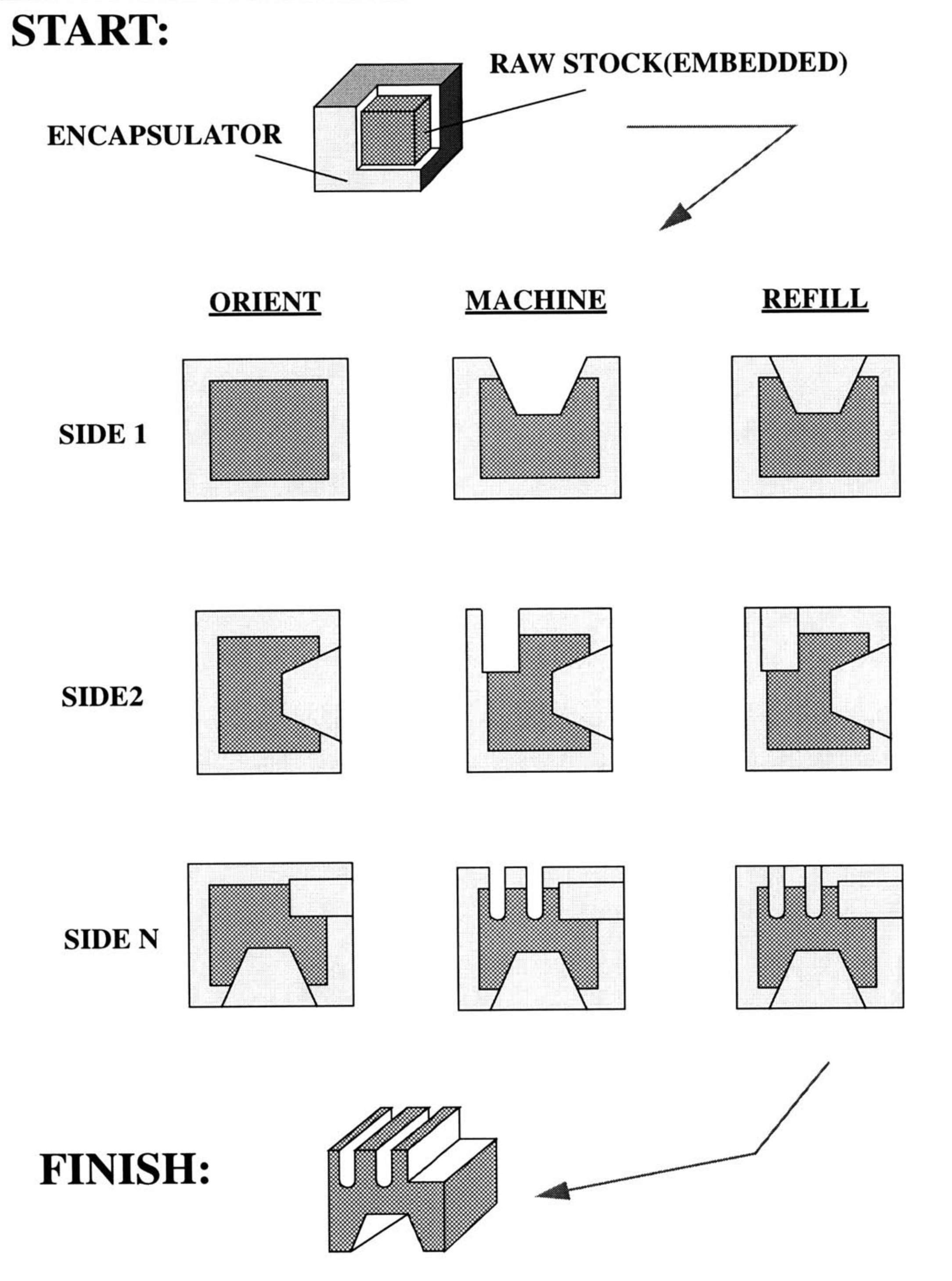


Figure 2.1 Encapsulation process steps

2.2 Work at Berkeley

The concepts developed at the University of California, Berkeley led to what Professor Sanjay Sarma had named RFPE, Reference Free Part Encapsulation. The basic process that he developed is essential what is shown in Encapsulation process steps. The key idea behind RFPE was to automate the fixturing process using encapsulation techniques but without the use of locating dies, hence the name "Reference Free." [Sarma 95] Sarma proposed that only blocks without any machined featured be encapsulated. Since no features existed on the encapsulated blocks, the determination of their precise orientation and location was unnecessary. When the encapsulation assembly was placed into the machine tool and it's first features were machined into the stock, the molded walls of the encapsulation would be used to locate the part encapsulated within. Thus, as long as those molded walls remained partially intact, the locational data of the fixturing setup would never be lost.

Professor Sarma also identified many of the problems that would hinder the encapsulation process. Thermal drift, shrinkage during the molding process, and strength issues of the encapsulator were the three most critical hurdles. In order to combat these problems, he proposed variations in the RPFE process that would minimize their effects.

2.2.1 Thermal Drift

One of the major challenges to remolding a workpiece accurately was the thermal drift effect. During the remolding process, the newly introduced encapsulation material raises the temperature of its surrounding enough to soften the pre-existing encapsulator surrounding the block. This softening allows the workpiece to shift a few thousands of an inch, thus destroying the accuracy/repeatability of the entire setup. This effect tends to occur when the encapsulator is a non-eutectic material. Having a broad phase transition temperature range instead of a sharp melting point, the encapsulator must be superheated far above the transition temperature range to insure that the encapsulator will readily flow when injected. When this superheated encapsulator comes into contact with the already encapsulated workpiece during a remolding stage, it raises the workpiece's temperature to above the start of the phase transition temperature, allowing the existing encapsulator to soften. These effects are further exacerbated if the encapsulator possess a low thermal conductivity. Heat then becomes trapped inside the mold allowing the encapsulator to reach higher temperatures and remain there for an extended period.

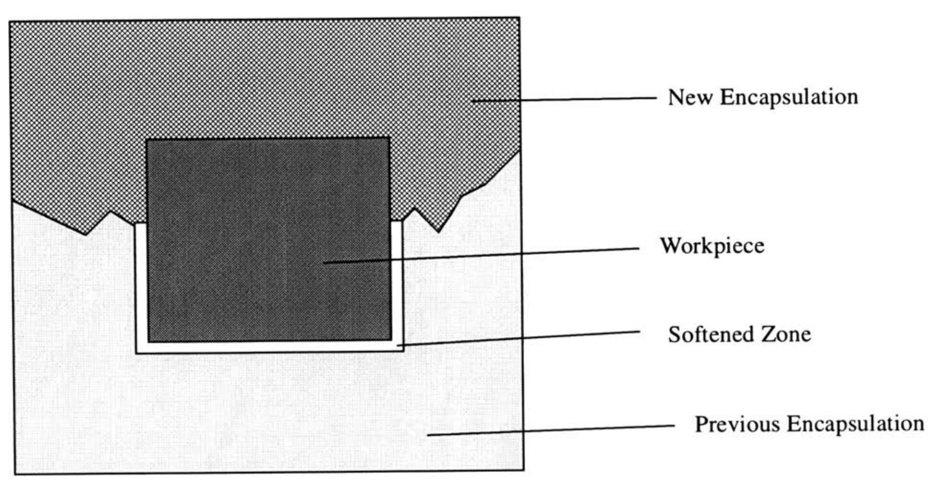


Figure 2.2 Illustration of the thermal drift effect during remolding

2.2.2 Deformation

The general trend of low melting temperature encapsulators is their lacks of strength and hardness compared to that of the workpiece they encapsulate. During milling procedures, deflection and deformation of workpiece and encapsulator is possible if it is not properly supported. However, deflection is usually minimized by the fact that the surface area contacted between the workpiece and encapsulator is so large. [Sarma 95] There are no stress concentrations or point loads between the workpiece and encapsulator. Therefore, a feasible encapsulator can possess a yield strength and modulus considerably less than the stock that it encapsulates given that a sufficient amount of surface contact exists between the stock and the encapsulator.

2.2.3 Shrinkage

Another major challenge to maintaining accuracy in the molding is that of controlling shrinkage of the encapsulation material. Shrinking can cause pitting and sinks on the surfaces of the encapsulation and porosity inside. Also, the encapsulator tends to pull itself way from the mold walls during the cooling process, creating bowed, curved surfaces which can not be used as locational datum planes. To solve this problem, the

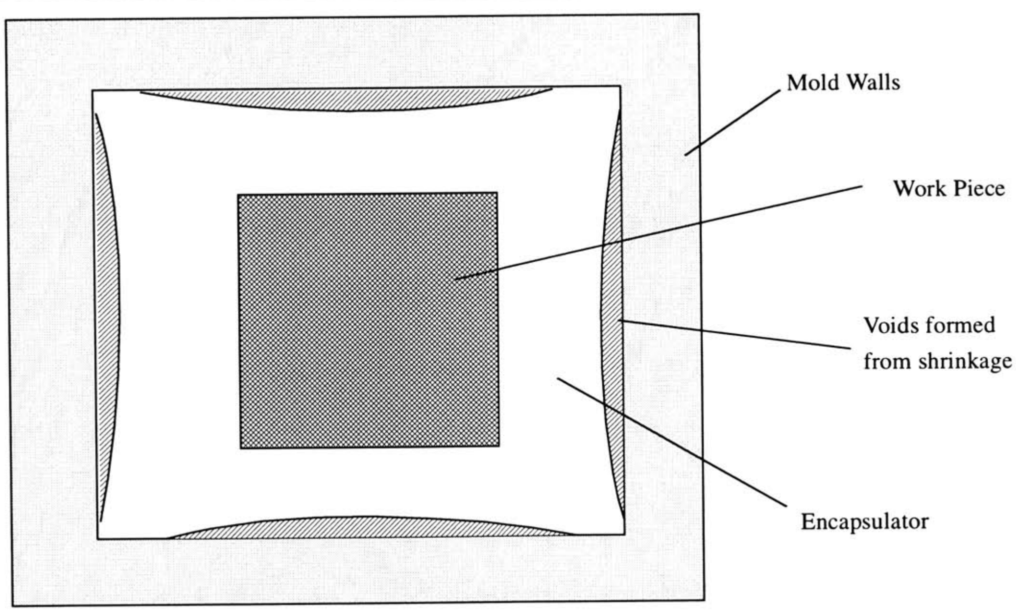


Figure 2.3 Illustration of shrinkage effects on molded walls

encapsulation assembly can be subsequently machined after they are molded to flatten out their walls. However, these add steps to the overall process which are undesirable.

Therefore, modified RFPE techniques were developed to combat this specific problem.Variations in RFPE.

To combat the shrinkage problem, Sarma proposed two alternative methods for fixturing parts using encapsulation. Both techniques would no longer use the molded encapsulator walls as the reference datums. Instead, the "Cage" RFPE technique used a steel, spring loaded rectangular cage as a hard surface to locate off of. The springs on the cage would allow it to expand to conform to the mold. The encapsulator would be poured into the molded and would retain the workpiece, supporting it between the cage struts. The shrinkage of the encapsulator was no longer a factor in determining the fixturing accuracy. The encapsulator served to support and immobilize but was no longer used to located the workpiece.

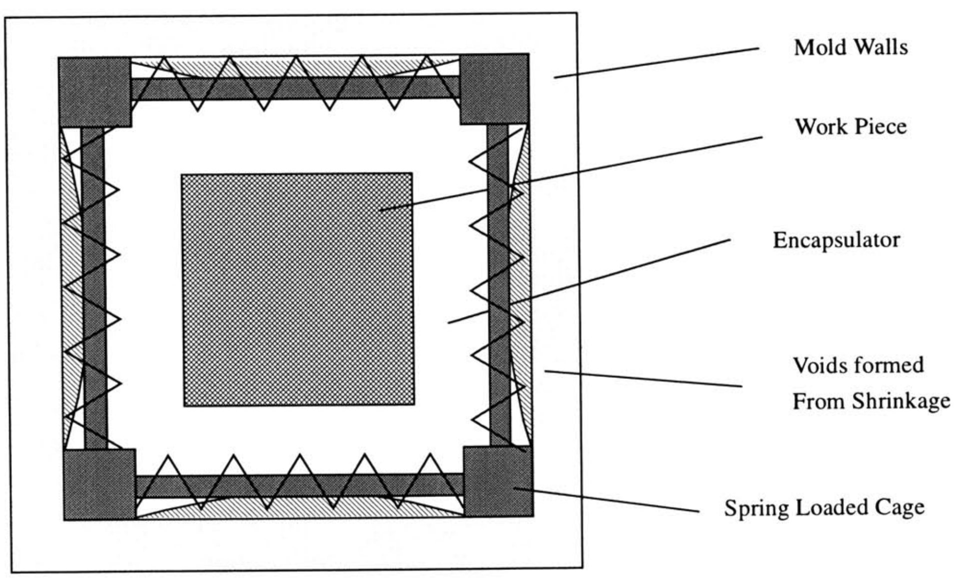


Figure 2.4 Illustration of Cage RFPE

The second method was the called "Stock-Enclosed" RFPE [Sarma 95]. Like the cage version, it still used the encapsulator to support and immobilize the workpiece. However to locate the workpiece, it used the workpiece itself. The workpiece would, of course, need to be machined into a perfect rectangular cube in order to use its walls as location datums. Then, features that were machined into the stock would refilled by pouring the encapsulator directly into the pocket machined into the stock.

Both of these methods have their limitations. Most notably, both reduce the accessibility to the actual workpiece. The need to maintain a cage or stock around the encapsulator prohibits machining in several key directions. Also, the Stock Enclosed RFPE required that the stock be pre-machined into a block form before the actual machining process could begin, thus adding steps to the process.

2.3 Encapsulation in Industry

Phase change encapsulation fixturing is hardly a new idea in the machining and manufacturing industry. One of the most prevalent uses of phase changing fixturing is in the aerospace industry. Since the invention of the turbine engine, manufacturing the turbine blades have proven to be a particularly challenging task and fixturing these oddly shaped turbine blades for machining has obtained a fair amount of attention. Many of the industry's technological leaders have turned to encapsulation to fulfill their fixturing needs.

Pratt & Whitney's North Haven, Connecticut facilities uses a modified encapsulation process to fixture post-cast turbine blade in order to grind the tail feature that allow the blades to be inserted into the main turbine hub. The plant itself was built in 1953 but only started to use encapsulation fixturing in the early 1970's. The entire factory floor is setup to handle every facet of encapsulation. Special workholding devices have been design to locate and hold the turbine blades before it is encapsulated. Each encapsulation cell is manned by one operator, inserting new blades into the workholding/molding device and removing an encapsulated one roughly every 5 seconds. These encapsulated blades are then moved to a different cell where they are automatically located and fixtured into a grinding machine. Once machined, they are then transported to the encapsulation removal stations. Loaded into a high pressure steam chamber, the encapsulation surrounding the turbine blades are melted off and then inspected for residue [Sprenkle 96].

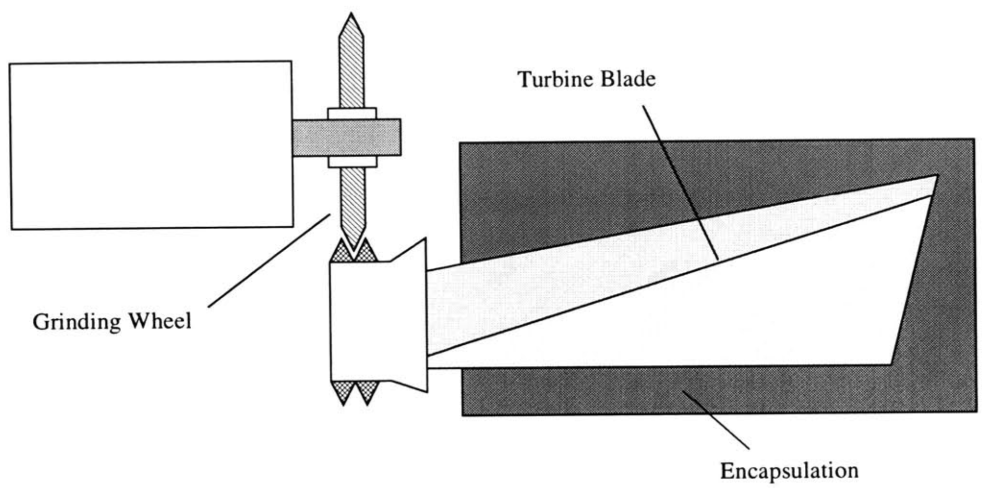


Figure 2.5 Encapsulating turbine blade for machining processes allows a less complex fixturing system to accommodate odd geometries.

2.4 Material Selection

One of the key factors to the success of designing an autonomous fixturing system using encapsulation is the selection of the encapsulating material, the encapsulator. Thus far, the materials that have been investigated are fixturing polymers such as Rigidax™ and Freeman™ machinable wax, fusible alloys such as alloys of tin and bismuth, and various types of higher melting temperature engineering plastics such as acetels, acrylics, nylons, and polycarbonates. In choosing the encapsulator, one has to take into account the hardness and stiffness of the material, its machinability, its thermal conductivity and moldability, the quality of its adhesion to the workpiece, its melting temperature, its coefficient of thermal expansion, its ease of reclaim, the stability of these properties after numerous reclaims, and, of course, its price and its safeness.

2.4.1 Selection Criteria

The primary objective in selecting an encapsulator is to minimize the molding cycle times while also maximizing the quality of the moldings. The quality of the molding can be defined by many parameters. It can be define through such metrics as the accuracy and the level of surface finish attainable through molding and through machining once encapsulated. Furthermore, these two objectives are balanced by a third, that of minimizing the cost of support equipment, such as the injection machine, that must handle and deliver the encapsulator. And of course, all these considerations are blanketed with the need to produce a safe and healthy working environment.

The material properties that we have identified to be important are the following:

•**Yield Strength/Young's Modulus**-For precision machining, the encapsulator should have a high Young's modulus, but have a fairly low yield strength. This allows the encapsulator to be more machinable while also minimizing the errors in deflection caused by the cutting forces in the machining process.

•**Thermal Conductivity**-A high thermal conductivity aids in cooling the encapsulator quickly once molded, allowing the molding cycle time to be reduced. However, high conductivity will result in a high rate of heat loss and a likelihood of freezing during the molding process if it comes into contact with a cold surface. This can result in short shoots or scarred surfaces. Maintaining a warm mold will thus be a functional requirement of the molding system if a high conductivity encapsulator is used. This shall be discussed later, in Chapter 3.

•**Viscosity**-A low viscosity allows for easier delivery of the encapsulator to the mold at lower temperatures. Less pressure would be needed to deliver the encapsulator, thus reducing the cost of the injection piston system.

•**Melting Temperature**-A lower encapsulator melting temperature allows for less complex molding devices. Since the temperatures on the mold and delivery systems do not need to reach as high, there can be less insulation around the heaters, and the heaters themselves need not be so large or use as much power. In addition, since machining is performed on the encapsulation assembly at room temperature, a lower melting temperature reduces the temperature change the encapsulation must endure between molding and machining. This reduces the effects of thermal strains caused by the mismatch in the coefficients of thermal expansion, between the encapsulator and the stock within.

•**Eutectic/Non-Eutectic**-Eutectic encapsulators have obvious advantages in terms of avoiding the problem described in Section Thermal Drift. The encapsulator need not be super heated to ensure low viscosity during injection and subsequently would not soften existing encapsulator that already surround the workpiece. However, there are drawbacks in using an eutectic alloy. Most notably is the sealing, dipping difficulties and the flash that arise around mold mating surfaces. Eutectics exhibit a sharp change in viscosity at its melting temperature. It is very difficult to control a eutectic's viscosity through temperature. Eutectics can, thus, only be used in either a hard solid which will not flow and a low viscosity liquid that will readily flow. On the other hand, a non-eutectic alloy's viscosity, because it has a melting range where it gradually softens with the increase in its temperature, can be control quite easily through temperature. The alloy could be injected at a temperature where it was a fairly viscous liquid and thus would not readily drip or flash. Encapsulation using a higher viscosity encapsulator would allow less stringent flatness specifications on mold mating surfaces. And when the mold is open, the surface tension of the high viscosity encapsulator would be enough to prevent dripping from the gates, reducing the need to design in a valve at the gates.

•**Coefficient of Thermal Expansion**-As stated in section Shrinkage, it is advantageous to minimize the coefficient of thermal expansion in order to reduce shrinkage after cooling. In fact, the encapsulators should be formulated with a slightly negative CTE's so that blocks will expand to fit the molds more accurately upon cooling.

•**Chemical Interaction**-It is important that the encapsulator can be fully melted away from the workpiece once all the milling operations have been performed. The encapsulator must not disturb the surface finish of the finished part, alter its molecular state, or become permanently bonded to the workpiece. Trace amounts of the encapsulator in the workpiece can render the part unless for its intended application.

•**Damping**-Encapsulators that can add extra damping to the fixturing system will reduce chatter during machining and thus increase the overall accuracy of the machining process.

•**Safety and Health**-Besides obvious reason, an encapsulator should be chosen such that it does not possess particular danger to those who work with it because it will increase system and process costs and complexity. Dangerous materials require special equipment to handle and treat it. Cleaning apparatus needs to be installed to insure that waste from the process does not infect the environment. And a variety of safeguards must be set in place to deal with accidents and mishaps.

•**Surface Energy/Adhesive Properties**- Lastly, a less obvious material property is that of the quality of adhesion of the encapsulator to the stock. Without fairly good contact between the encapsulator and the workpiece, gaps will form from trapped air bubbles and shrinkage. When machining is done, capillary action will tend to suck machining coolant between the block and the encapsulator. As a result, the block will float slightly and jitter as it is machined. Good adhesion between the block and the encapsulator will prevent this by firmly anchoring the workpiece to the encapsulator and ensuring good contact.

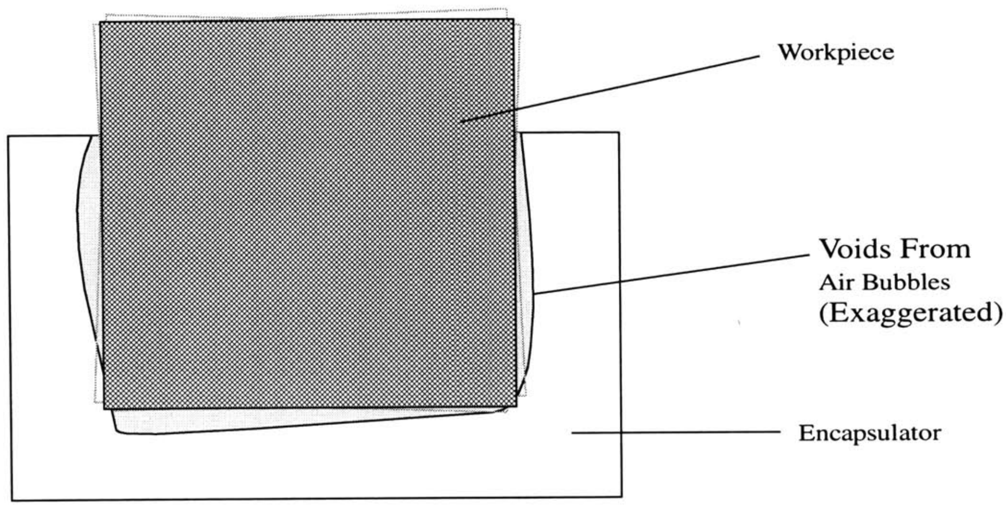


Figure 2.6 Illustration of voids that are often formed by trapped air bubbles or shrinkage of the encapsulator

2.4.2 Fusible Alloys

This research has primarily relied on a Bismuth/Tin eutectic alloy for encapsulation. Widely available, this eutectic binary alloy is composed of 58% Bismuth and 42% Tin. The alloy has a low melting point of 281 degrees Fahrenheit. It has a reasonably high Young's Modulus of 7.5GPa and an adequate yield strength of 60MPa. It's thermal conductivity is 18.4 W/m°K. It's thermal expansion efficient is 15 e-6/ °K. It has very good stability. It's main detractor is that it has a high surface energy and thus will not easily wet most metallic materials and other materials that will easily oxidize. Methods for combating this problem will be discuss later in chapter 5.

Tin/Bismuth alloys fall wintin a braod class of alloys called fusible alloys which are low melting temperature metallic alloys. In general, they are used as solders. Most contain lead and many contain cadmium. Both lead and cadmium are carcinogenic. Thus developing an encapsulation process using an alloy composed of either will not only become extremely hazardous but also cumbersome to the process. Many safety regulations and guideline must be followed to the letter. Thus, the encapsulation alloy was chosen specifically because it contains no substantial amounts of lead or cadmium. The fact that it also happens to be an eutectic and matches may of the other criterions is fortuitous. There are other combinations of the bismuth/tin binary alloy that are potentially useful in our study. There is a 40/60 bismuth/tin alloy that possesses a melting range on 281°F to 335°F. It has many merits as well to our application that the eutectic does not possess. For example, its thermal conductivity is twice a large, at about 29.6 W/m°K. The growth and shrinkage of the 40/60 alloy is also significantly different. There has been little experimentation performed on the 40/60 alloy. It will be interesting to observe its performance. We shall pursue this at a later time.

2.4.3 Fixturing Polymers

While fixturing polymers can be easily machined, melt at low temperatures and provide considerable damping to the fixturing system, they have low thermal conductivity, high shrinkage, and very poor mechanical strength. Maintaining a good surface quality on such a soft material would be extremely difficult if not impossible. The low conductivity and high shrinkage often causes sinks and bows on the surface of the moldings. What is more, there is a severe thermal expansion mismatch between the machinable polymers and most metals that will cause the encapsulation to crack and disintegrate upon cooling around its workpiece. The Rigidax™ machinable polymers possess fairly good adhesive qualities, adhering to metals and other materials reasonably well. However, this visco-elastic and adhesive effect causes the material to gum up endmill flutes and results in poor machinability. For this application, fixturing polymers has proved to be unattractive.

2.4.4 Engineering Plastics

Engineering thermoplastics, which have been used in industry as injection molding materials, are not much better suited for encapsulation. Their high shrinkage is a major detractor. While this high shrinkage can be alleviated by using a packing routine during the encapsulation/injection process, sinks and bows are still visible when the thickness of injected parts becomes substantial. While their mechanical properties are very appealing, they are non-eutectic and have very high melting temperatures. Nylons™ melt at 440°F and Actels(Delrin™), 495°F. Their thermal conductivity is low, averaging about 2.3 W/m°K. And in general, they are difficult to machine compared to the other two material types. Their high strengths generate considerable heat which can not be dissipated due to their low thermal conductivity. As a result, endmill flutes often cog when the material removal rate is too high.

2.5 Advantages of Encapsulation Over other Fixturing Methods

Having familiarized ourselves with encapsulation as a fixturing process, it is appropriate to return to the beginning and develop the reasons for developing our universal fixturing system using phase change fixturing methods. Within this section, the focus shall be to discuss the advantages of fixturing through encapsulation and its ability to accomplish tasks that no other fixturing process could.

2.5.1 Ease of Automation

Encapsulating the raw stock constrains the part shape to a generic norm, in this case a rectangular block with perfectly perpendicular walls. This constraint allows for a more intelligent workholding design. It allows one to easily design an algorithm that will carry out accurate/repeatable workholding of any arbitrarily shaped part. References are continuously maintained during setup changes using the boundaries of the filler block, which are independent of part features. Working holding can thus be easily automated since the fixturing system need only interact with that one generic norm and not thousands of different geometries.

2.5.2 Machining Thin Members and Odd Shapes

Encapsulation can be used to fixture almost any arbitrary shape. Delicate features, such as spring elements, ribs, and thin walls, can be machined. Encapsulation fixturing gives us the ability to machine features onto those spring elements without worry of deflection or deformation of those features. As shown in Illustration showing toolpaths for machining special elements with the aid of encapsulation fixturing, the encapsulation can be filled so that it directly supports the feature while it is being machined. The encapsulator can fully support thin elements regardless of their location within the workpiece. For these special features, the remolding pattern must be carefully planned. Only one side of the feature can be cut in one pass. The workpiece must be remolded and the feature refilled before machining can proceed to the next side. It should not be difficult to create CAD/CAM programs to identify these thin features, which have large length to width ratios, and automatically plan the proper tool paths and remolding sequences. This innovative CAM scheme is discussed more in chapter 5.

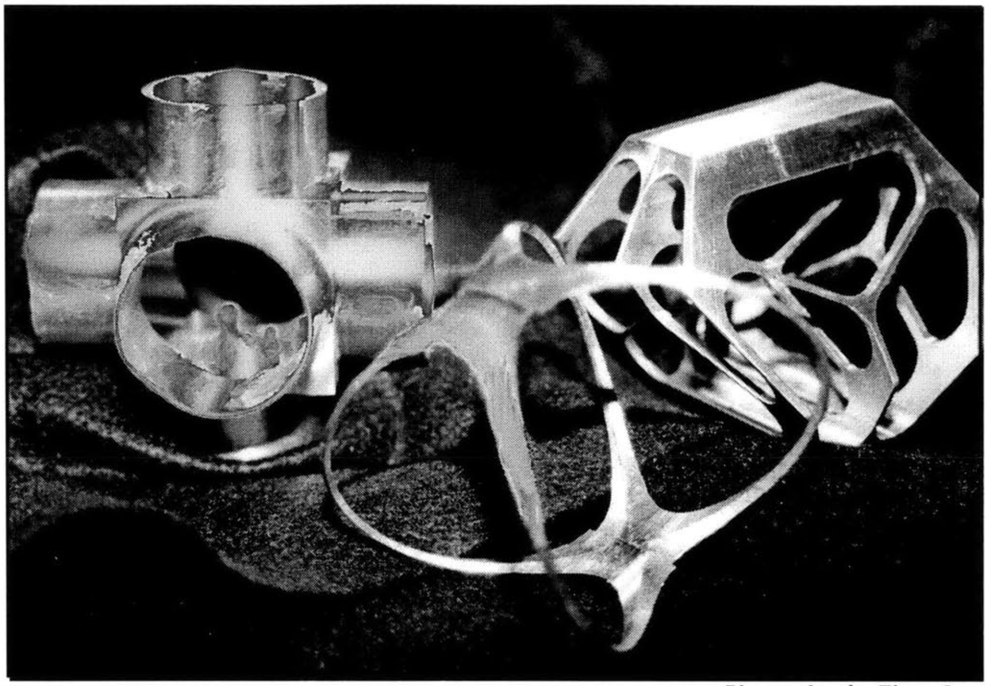


Photo taken by Elmer Lee

Figure 2.7 Photograph of sample parts machined using encapsulation fixturing:
Parts are made of AL 6061-T6 on a 3 axis Cincinnati Milicron 7VC

Parts that once needed to be machined separately, because of fixturing constraint, and then assembled later, can now be machine out of one piece, cutting assembly time and costs. Ordinarily, the three tube elements shown in the back left in Photograph of sample parts machined using encapsulation fixturing: would be machined separately and then welded together. Here, encapsulation allows the machining of all three tube elements from the same piece of stock. The tube walls are all less than 0.01" thick and more than 1.00" high. The orb shaped part, shown in the front in Photograph of sample parts machined using encapsulation fixturing:, and the intricate webbed part shown right back in Photograph of sample parts machined using encapsulation fixturing: were both manufactured on a 3 axis milling machine, out of a single piece of stock, despite their delicate spars. Without encapsulation, both parts would be extremely difficult to fixture

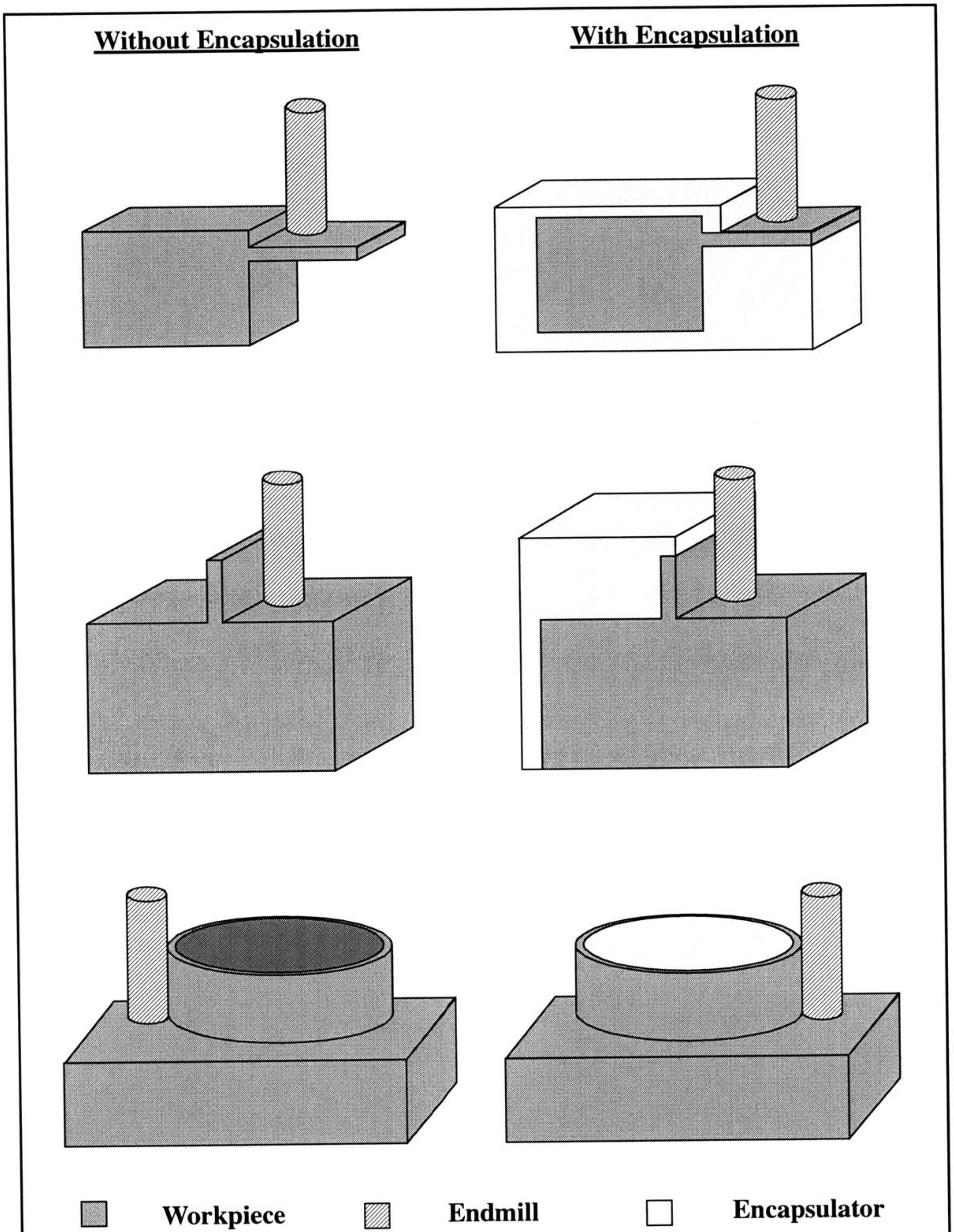


Figure 2.8 Illustration showing toolpaths for machining special elements with the aid of encapsulation fixturing

and machine. Most likely, more expensive, time consuming manufacturing methods, such as wired electro-discharge machining, would have been used to manufacture these parts had encapsulation fixturing not been available.

2.5.3 Developing manufacturing processes without hard tooling

While this encapsulation fixturing process was never designed to replace hard tooling in a mass production environment, it can be used during the preliminary stages when developing a mass production facility. During the preliminary testing of a manufacturing plant, machine tools and other equipment are constantly being changed and retrofitted in order to optimize plant and increase the production rate and efficiency. Unfortunately, while machines can usually be sold or redistributed to others parts of the plant, changes in the plant layout usually result in changing to new types of tooling and fixturing system, leaving the old hard tooling, that was specifically designed for that single process, useless.

Instead, manufacturing engineering can develop their processes using the same universal fixturing we are developing. Once the machines and support equipment have been debugged, the encapsulation fixturing can be replace with permanent hard tooling. Such a practice removes the possibility of scrapping a piece of hard tooling because of equipment changes.

2.5.4 Machining Parts in Small Batch Sizes

The next frontier in manufacturing is likely to be in single part production, that of producing goods customized to the individual, on demand. It will be the ability to manufacture one part as inexpensively and as efficiently as one thousand parts that will revolutionize the industry. An automated universal fixturing system will play an important role in achieve these goals.

Developing our fixturing system through encapsulation brings us one step closer to those goals. Once encapsulated, different parts are treated by the workholding device as the same. Thus, multiple parts can be machined in the same fixturing setup. There is no need to change setups and there will be no down time for the machine. With encapsulation, we can turn a mass production machine into a rapid prototyping machine.

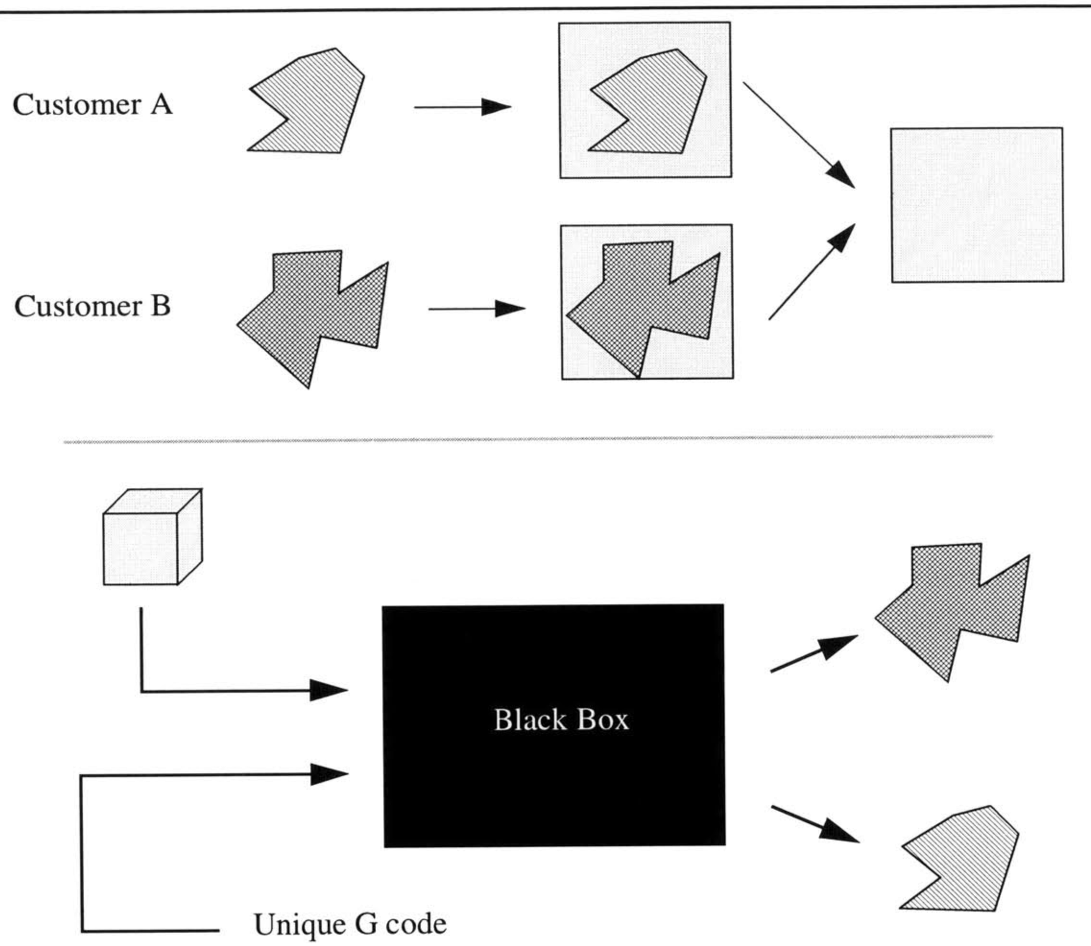


Figure 2.9 Illustration of encapsulation fixture's ability to transform 2 different parts into one generic norm:
Once Encapsulated, "the black box" can treat customer A and customer B's parts as identical. Their only difference will be the G-code needed to control the "black box." Depending on the G-code, either part can be manufactured with equal ease.

Chapter 3: Design Process of an Encapsulation System for Fixturing Applications

This chapter describes the process by which the encapsulation machine has been designed. It shows the train of thought and logic, and illustrates some of the key design paradigms which were adopted. The design problem was organized in terms of functional requirements and their corresponding design parameters to separate this large complex design problem into parts which are smaller and more tractable.

3.1 Primary Functional Requirements

The first step in any design process is to identify the key problem(s) and hurdle(s). I have done so by identifying the functional requirements(FR) of the design [Suh 90]. It is important to note that at this stage of the design, only the problem is discussed. We will do our best to keep solutions to those problems, or design parameters, out of our thoughts and efforts at this point. Of course, it will also be important to make certain assumptions to limit the focus of our problem. Otherwise, the design process will be overly complicated with superficial details.

Furthermore, these functional requirements have been organized in a hierarchical manner, moving from general functional requirements to more specific ones. In this manner, it will be easy to separate those functions that are related or dependent on each other and those that are not.

For the design of an encapsulation machine, the primary functional requirements are as shown.

- **Melt the Encapsulator and Store it for use**

  In order to be used, the encapsulator must be transformed from its solid form to its liquid form. Assuming that heating will not be quick enough such that each shot can be melted just prior to injection, a fair amount of the encapsulator will have to be melted and kept molten until it is ready for use.

- **Deliver the Molten Encapsulator from the storage unit to the molding device**

  Assuming that the storage unit and the molding unit will be separated, it will be necessary to transport the encapsulator from one to the other. Considerations such as how to maintain the encapsulator molten, what pressure is needed to be delivered and how quickly need it be delivered are all sub FR's that will be considered later.

- **Mold the encapsulator**

  Though fairly obvious, this functional requirement will have a great many sub FR's that further divides this part into smaller parts of the design. This FR should be subdivided into other FR's dealing with the molds, the clamping device, and the interface with the delivery system.

It should be noted that decoupling a design into different FR's is purely for the designer's convenience and is done solely at the designer's discretion. There is no absolute algorithm on how to separate FR's and sub FR's (there are, of course, better and worse ways to develop them). One can expect, for any given design problem, that two designers can choose to decouple the functional requirements in different manners, each leading to a viable design solution.

I have chosen to decouple the encapsulating machine into three parts based on considerable experimental experience and intuition. You will see, later on, that each of these three functional requirements are transformed into three easily distinguished design units or machines. I find that designing by drawing boundaries that delineate the overall design into smaller more manageable unit allows me to design one part without too much concern for the functions of the rest of the machine. This, of course, is artificial. For any process or machine design, all its parts must function harmoniously, communicating with each other at all times. To design one unit of a machine without any consideration of the other parts would be foolish.

Nonetheless, the decoupling of the functions of a machine does allow one to satisfy one function at a time by imagining that the rest of the design remains given and fixed. Afterwards, one can move on to another function in much the same fashion. However, it is necessary to revisit the previous functional requirements to assure that no conflict has risen and that all the functional requirements still remain satisfied. Thus, this design process can be thought of, not as one pass approach, but as an iterative one.

3.2 Expanding into Sub-Functional Requirements

Now that we have laid down the overall scheme of the machine, that is separated the machine into its key components, we will then tackle each individually. It is necessary to elaborate on each of the primary functional requirements and to build a more complete list of the tasks each units must accomplish. They are as shown below.

3.2.1 Melting the Encapsulator and Store it for use

The sub-functional requirements are:

- **Allow for fast warm up**

  The melting of the encapsulator will not directly effect the molding cycle time of the entire machine. Nonetheless, the warm up time should not be extraordinarily long or it will become burdensome during production in cases when the system must be powered down and restarted, as on occasions when cleaning and maintenance work must be down. Though not a concrete number, setup times of about 1 or 2 hour would be acceptable.

- **Easily maintained and serviced**

Over the life of the machine, it will of course need to be maintained and serviced. When a different encapsulator must be used, it will be necessary to purge the system of the previous encapsulator material. Thus, ease of removal of the encapsulator and cleaning will be a clear performance attribute. While this functional requirement will need to be discussed for all parts of the machine, the transfer unit and the molding unit, it will be focused in this unit of the machine because the bulk of the material will remain in the storage area.

3.2.2 Deliver the Molten Encapsulator from the storage unit to the molding device

- **Ensure that transfer line never freezes up-that flow is always maintained**

Because the encapsulator that will be usually employ in the encapsulation process is a metallic alloy, having a high thermal conductivity, it will readily lose heat upon contacting a cold surface. Freezing and lockup of the transfer line will thus be a key concern and a major problem to overcome.

- **Facilitate molding using pressure**

It will be necessary to perform the molding under pressure. This will improve the surface finish of the molding by allowing the encapsulator to conform to the mold and workpiece surfaces more accurately. Molding under pressure will minimize the shrinking of the encapsulation. It will allow the mold to be fill quicker and the molded to be designed using smaller gate sizes, thus allowing the encapsulation assembly to be more easily removed from the mold. Our experiments have shown that the use of pressure is vital to improving the accuracies of the molding and the overall performance of the fixturing process. The advantages of molding under pressure will be further discussed in later sections.

3.2.3 Mold the encapsulator

- **Ensure Safety and Economy**

We must ensure that the molds seals properly and that no spillage occurs. It will also be necessary to insulate the heaters to conserve heat energy and prevent accidental burning of the operators should he touch the hot surfaces.

- **Maintain a Low Cycle time**

The cost and utility of a machine is directly dependent on its cycle time. The faster a machine can produce a particular item, the more useful and worthwhile it will be to purchase. Thus, optimizing the machine so that its cycle time is as low as possible is another key task. To do so we must examine the cycle itself. Within the cycle, stock must be delivered and placed inside the mold, the mold must be heated to the desire temperature, the mold must be securely closed, the encapsulation must be at the proper temperature and ready to be delivered. Once the mold is closed and secure, the encapsulation needs to be delivered. Once filled, the encapsulation and the mold need to be cooled to the proper temperature, and then extracted from the mold. Finally, the mold must be made ready to accept the next piece of stock. From these steps, we can develop more precise functional requirements that have the effect of reducing the cycle time. These are shown below.

- ***Fast thermal cycles of the molds***

Here we must consider the heater and cooling plate placement. We must place thermal sensors as close to the targeted area to reduce thermal abbe errors. We must prevent the gates from freezing up, else they will need to be remelted or cleared before the next cycle begins. And we must minimize the temperature change the mold must experience with in a cycle.

- ***Allow for quick and easy placement and removal of encapsulation assembly from the mold***

We must consider how to close and open the mold quickly, but also allow the placement and removal of the part with equal ease.

- **Achieve a High Quality Molding**

This function can be further sub-divided into the following

- ***Center workpiece during Molding***

Though it is not critical to know the exact location of the stock in the encapsulation. Ensuring that it is fairly well centered within the encapsulation allows us to be more efficient when machining our encapsulation.

- ***Reduce Shrinkage***

As described in the previous chapter, shrinkage is a one of the leading causes of accuracy problems in an encapsulation

- ***Achieve Good Surface Finish***

Pits and bumps on the surface will not allow us to use the molded surfaces as locational datums

- ***Achieve Good Accuracy***

All adjacent mold walls must be perpendicular to each other in order to use those walls to locate the encapsulation inside the milling machine. Thus the mold must be manufacturer by means that will ensure its accuracy.

- ***Prevent the encapsulation from getting wedged inside the mold***

Because it is necessary to use the molded walls as a locational datum, the formation of these walls with a draft angle is prohibited. However, with no draft allowed in the mold, the removal of the encapsulation from the mold becomes impossible for a one piece mold. Once solidified, the encapsulation expands and wedges itself tightly inside the mold. We must place the parting line of the mold in the correct orientation and location such that it will not allow the encapsulation to become jammed inside.

3.3 Decoupling into Three Separate Machines

3.3.1 Melter Device

In designing this particular element, there were no real challenges or high hurdles to overcome. Heating and melting low melting temperature alloys has been widely done in industry. Thus, the focus of the design process is obtaining standardize parts and products that I could assemble to form my heating/storage unit. Particular attention is paid to the possible interfaces with the deliver system, the storage capacity and the power output of the tank. Safety and quality is also a big concern as is cost and delivery time of the products.

3.3.2 Injection Machine

The injection machine has proven to be a slightly more difficult item to find in industry. While injection molding machines are fairly common pieces of equipment, there are none that match the specification desired for encapsulation. The main reason for this is the need for a machine that could inject at a fairly low pressure but also with a very large shot size. Standard injection machines could not match the 250 psi or lower injection pressure with a 55 cu in shot size specification. Most were built to deliver their injection at 10,000 psi of pressure with maximum shot volume of only a few ounces. In addition, these machines cost hundreds of thousands of dollars and provide functionality that were unnecessary. It is thus evident that I would have to design my own injection system and have it manufactured customized to out application.

3.3.3 Clamping System

The clamping system has to be developed in its entirety. In order to be more cost effective, the clamping system has to accept custom design molds of various sizes. It needs to clamp different sized molds, always insuring perfect sealing and the correct clamping forces. As with other clamping unit, such as those in an injection molding machine, it needs to provide easy access to the encapsulation chamber to allow the placement and removal of the molded part. Also, it is necessary to place heating and cooling units within the machine to decrease the thermal cycle times.

3.4 Developing Molds for Encapsulation-Decoupling into Three Machining Strategies

It was apparent from the beginning that one mold could not produce encapsulations that would satisfy all the machining requirements needed for a truly universal fixturing systems. Different sizes, much like the different sizes of paper for a photocopying machine, are needed to efficiently machine all the possible parts that ranged from 1 inch size to the 6 inch size. In addition, not only is it necessary to create discrete sizes of encapsulations, it is also necessary to produce different types of molds for the 3 distinct machining strategies. By splitting the machining into these strategies we increase the efficiency of the encapsulation fixturing without increasing the complexity of the encapsulation process too much. The three strategies are described below.

3.4.1 3-D milling

This is the broadest machining strategy. With this encapsulation, one can machine features in any orientation of the part. In any of the 6 orthogonal sides, a feature can be placed without any obstruction due to the fixturing. In this situation, the locational datum constantly change from setup to setup. Thus, it is necessary to keep track of them and insure that they stay true. This strategy is the most difficult to implement--the molding and the re-molding must be done with great precision. Yet it offers the most freedom and functionality. Because it is the broadest of the three, it has been this strategy that we have been using to introduce encapsulation fixturing. However, depending on the application, the other two strategies are be equally vital and useful to the successful and cost-effective implementation of a fully automated universal fixturing system.

3.4.2 2 1/2-D milling

Stepping one notch down in complexity, 2 1/2 D milling involves machining only 5 out of the 6 sides and many times only four sides of the encapsulation. In these situations, multiple setup are still needed but only one set of locational datums is use to locate the part for all setups. Usually, a fixturing element is embedded into the sixth unused side during the encapsulation process and it serves to locate the part while the encapsulation still serves to immobilize and support the workpiece. In this situation it is not necessary that the molded walls be formed or reformed with such tight tolerances. And thus, our molding devices need not be so complex or machined to such tight tolerances. In addition, because the molded walls are not being used to locate our workpiece, draft angles can be used in our molds to facilitate part removal. This allows us to remove the perpendicular parting line and build a single piece mold. Despite its many advantages, this strategy does obscure and prevent one direction from being machined and thus limits its use to only a certain class of parts.

This strategy can be compared to the "cage" and "stock-enclosed" RFPE methods Sarma developed at Berkeley. Both ideas use an external feature to locate the entire workpiece. However, while "cage" and "stock-enclosed" RFPE obscured parts of all 6 orientations, 2 1/2D encapsulation obscures only one side.

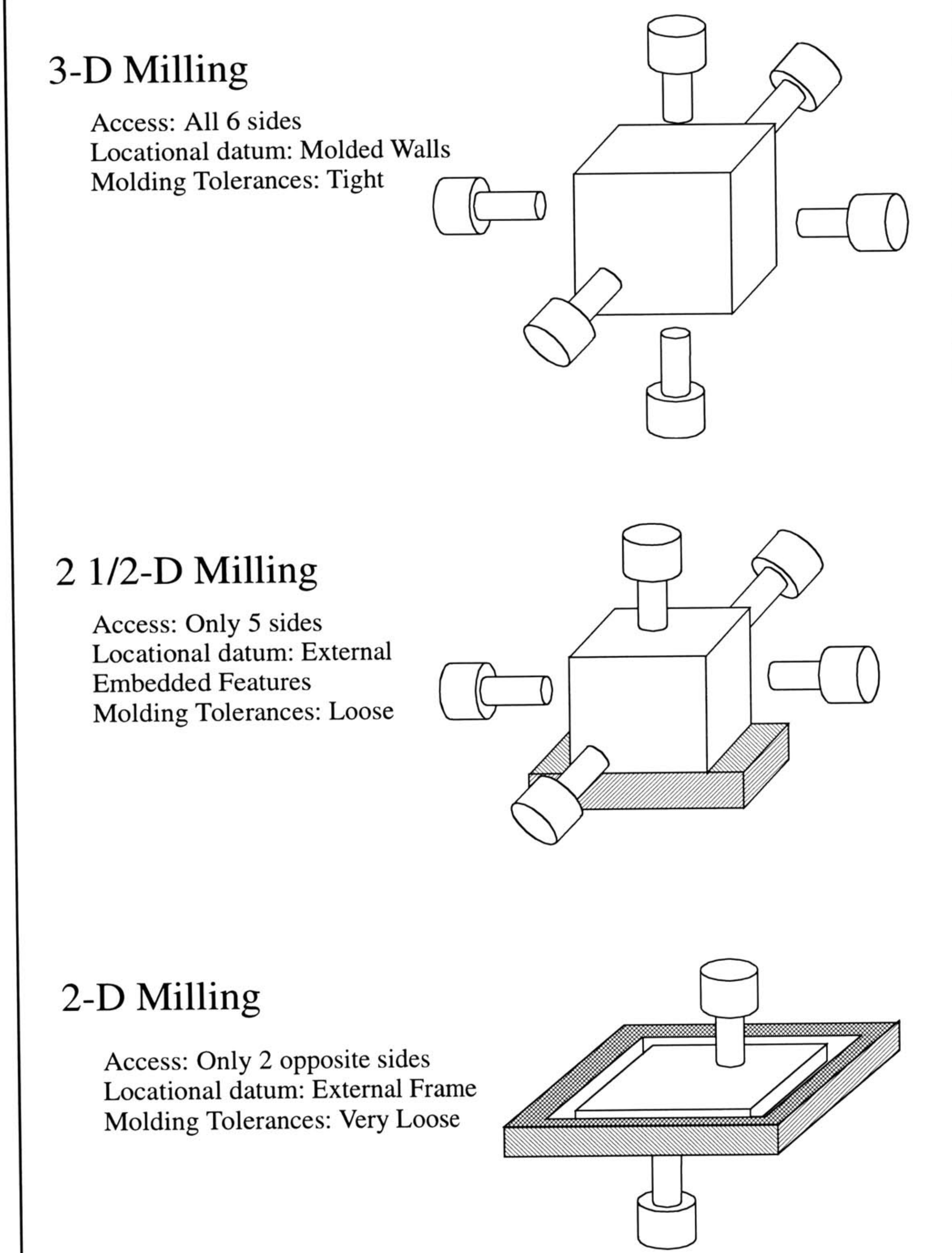


Figure 3.1 Illustration of the three fundamental machining strategies: 3-D, 2 1/2 D, AND 2-D

3.4.3 2-D milling

The most simple of the three machining strategies, 2-D milling involves placing features on only 2 opposite side of a piece of stock. Very similar to the 2 1/2-D setup, its locational datums never change, always obtained through some external feature embedded into the encapsulation. What is unique is that the stocks that will be machined are dominantly plate form. This allows us to simplify to mold design. In these cases, the embedded external features, used to locate the workpiece, can actually be used to form the mold itself. The entire structure is thus transport to and from the encapsulation machine and the machine tool. The internal pocket of the mold do not need to be particularly accurate since, during remolding, there is no worry about the encapsulation not fitting into the original mold. In this case, the encapsulation never leaves the mold. Parting lines for the mold lie in one plane, thus sealing can easily be accomplished using rubber gaskets. This is by far the most easily implemented strategy of the three. But, of course, it is only suitable for a small group of parts.

3.5 Key Design Considerations

Once the functional requirements of our design have been identified, it is necessary to develop embodiments of solutions that could successfully fulfill those FR's. Most times, the solution or embodiment that fulfills an FR is obvious, and thus decision making becomes trivial. In other cases, multiple solutions to a single FR are possible. It thus necessary to weigh each and choose the most appropriate paths to follow. In this section, we discuss two of the key design considerations we are faced with, present the solutions we choose, and describe the reason behind choosing them. Other, less significant decisions, are discussed and explained in the next chapter.

3.5.1 Actuators: Pneumatics vs. Hydraulics

Actuation is needed in the clamping system and in the injection system. In both cases, a linear actuator is needed. Thus, the use of a piston type actuator would prove to be the simplest and most cost effective means of providing motion. However, the question remains on whether the piston should be actuated using pneumatics or through hydraulics, as is used in industry when actuating injection molding and diecasting machines. Each method has its own set of advantages and disadvantages. The most important factor is that of cost and ease of implementation.

Hydraulic and pneumatics both require that a supply system be present to supply the actuators with the pressurize fluid. In a machine shop environment, the existence of a pneumatic system is almost certain. Machine tools and other equipment usually require a pneumatic source to function properly. However, it will not be as likely to have a hydraulic supply system present. Setting one up, which would involve installing an expensive compressor and laying down supply lines, would be extremely costly and deter the acceptance of encapsulation fixturing in the intended working environment.

The main reason for the use of hydraulics in industry is, 1) the superior reaction time and 2) greater pressure available. In our application, neither a fast reaction time nor extremely high pressures is necessary and thus does not justify the increase in costs hydraulic actuation would bring.

In general, hydraulics react almost instantaneously to an operator command while pneumatics have a time delay of about 1 second between switching the valve on and movement of the piston. The difference arises from the difference between compressibility of air and that of hydraulic fluid, which generally is an oil based liquid.

The lag in a pneumatic system will not affect the performance of the injector or clamp. Although this lag and the compressibility of air will tend to make the movement of the injector and clamp slightly jumpy, it certainly will not effect the quality of the molding nor the cycle time of the molding machine.

The greater injection pressure would allow us to fill the molds quicker, allowing us to maintain the mold at lower temperatures without worrying of short shoots or freeze ups. In fact, cold mold diecasting is commonly practiced in industry because the injections are performed at more than 1000psi. However, unlike injection molding plastics which tend to be extremely viscous and require high pressures to properly fill thin features of molds, or die casting, which is done at extremely high temperatures, and as a result, will loss heat at a higher rate, the encapsulation can be performed at lower injection pressures and at lower mold temperatures because the encapsulation material being used has a very low viscosity, 45mPa-sec (similar to water), and a very low melting point, 281°F.

Hydraulics are an unnecessary expense that we can avoid. An addition reason for choosing pneumatics is that of maintenance. Both hydraulic and pneumatic systems leak during the course of their usage. While a small leakage of a pneumatic system proves to be no problem, results in very little pressure drop in the system, and thus requires no extensive clean up, a small leakage of a hydraulic system proves to be a hassle. Cleaning the spill is necessary and patching the leak is a must since small amounts of leakage results in a large pressure drop.

It is with this reasoning that the actuation on the encapsulation machine is solely pneumatically driven. With this decision, we are able to keep costs of the machine down, utilize an already existing supply system, and keep the working environment fairly clean and noise free.

3.5.2 Delivery Systems-Pressure vs. Gravity

Of all the decisions to be made, the choice between a pressurized or a solely gravity-assisted delivery systems is the most important one, having the greatest influence on the direction of the design process. Encapsulation experiments conducted at Berkeley and the encapsulation fixturing done at the Pratt & Whitney plant were never assisted by a pressurized injection systems. Their encapsulation molds were open to the atmosphere, and the encapsulation was done simple by pouring the encapsulator into the mold with only gravity assisting to fill the mold. As a result, the surface finish of the encapsulations produced by the Berkeley group and by Pratt & Whitney's encapsulation process are fairly poor. The surface is marred by cold shuts. Cold shuts are surface defects caused by the premature freezing of part of the pour stream when it comes into contact with a cold mold surface. The cold temperatures prevents the rewelding of the frozen injection to the main body of alloy in the mold, preventing uniform solidification. Flatness of the encapsulation walls is not easily guaranteed using this process. There is no way to combat shrinkage when molding is only assisted by gravity.

The apparatus and setup required to perform open mold encapsulation, that is one without the use of a pressurized injection system, are very simple. Complex molding machines are unnecessary since very little clamping force is required to keep the mold closed during encapsulation. The molds are equally simple. Developing a good seal along the mold's parting line can be easily accomplished without requiring mold surfaces to mate perfectly. In fact, Pratt & Whitney's mold design allow gaps of a 1/16" between mating surfaces of the mold. Since the molds were cold and the pouring pressure negligible, the encapsulation would solidify quite readily upon contacting the mold surfaces, preventing it from seeping out of the large gaps.

With the addition of a pressure assisted encapsulation system, the complexity of the molding, clamping, and delivery system increases dramatically. It is thus necessary to weigh those complexities that a pressurize injection system brings against the added functionality and performance it offers. With the addition of pressure, the molds used for encapsulation must now be well sealed. All mating surfaces must be machine fairly flat, thus requiring expensive, time-consuming operations such as grinding and hand finishing. It is equally important, and difficult, to ensure that the delivery system be sealed well. It is essential that elastomer o-rings be used to seal the injection piston, which is subjected to the same pressure as the mold. Viton™ O-ring are the elastomer of choice because they are rated for high temperature applications up to 450°F. Other elastomers such as natural rubber would quickly degrade when subjected to our injection temperature. All hoses must be joined by liquid tight hose fittings, such as Swagelok™ systems or tapered national pipe thread (NPT) fittings, specially designed to withstand the elevated pressure. A robust clamping system is a must now. It must be able to deliver a significant clamping force and yet also allow easy and quick placement and removal of our encapsulation. Consequently, the molds must be design to not only withstand the added stresses of the pressurized encapsulation but the clamping forces as well.

The benefits of pressure diecasting over gravity diecasting and sanding casting have been well documented [Allsop 83],[Upton 82]. And because of the similarity of between our encapsulation system and a diecasting system, we too can enjoy the benefits of adding a pressure injection system. Dimensional accuracy is far superior. The effects of shrinkage is greatly reduced when we use the pressure to constantly pack the mold during the solidification cycle. This is especially important since the walls of the encapsulation are used to locate the workpiece. The added pressure also results in better gripping of the workpiece encapsulated. The use of pressure results in fewer, if any, gaps and voids at the interface line. The pressure drives air bubbles from the stock surface and forces the liquid encapsulation to conform better to the workpiece surface. The pressurize encapsulation essentially applies a gripping force to the stock that can be maintain once the encapsulation solidifies. Without the pressure, the workpiece would sit slightly loose inside. Preliminary testing has shown that a pressure injected encapsulation will be able to hold an encapsulated workpiece approximately 4 time better than that of a conventional encapsulation. And lastly, the added pressure allows us to mold sharper corners and allows us to encapsulate smaller features.

The use of pressure offers benefits to the encapsulation process itself. Using pressure allows us to fill the molds more quickly. We can thus shoot into a colder mold with less worry of pre-mature freezing or short shots. Pressure allows us to fully cover our mold so that all 6 sides can be molded. Without the assistance of pressure, air would be trapped inside a fully covered mold, producing air pockets and destroying the quality of the molded surface. Lastly, with pressure, we can force the encapsulation to travel into the mold through smaller gates. Smaller gates allow us to remove the gates knubs more easily.

Chapter 4: Elements of the Automated Encapsulation System for Fixturing

This chapter discusses the finer details of designing and building an encapsulation machine. Two encapsulation machines have been built. The larger one, whose dimensions are 29" wide by 62 " long by 56" high, was design to remain stationary in the laboratory environment. Its primary purpose is to encapsulate larger parts to perform testing and evaluation, in house. The smaller machine, approximately 25" high, 9" wide and 25" long, weighing less than 100lbs when filled with the encapsulator, was designed to be portable. It will allow us to test the fixturing system, outside of the laboratory, in actual machine shop environments. Below, I describe the manufacturing and assembly of these machines and discuss some of the practical and performance issues of each. The focus of this chapter will be placed on the larger machine. However, since the design of both machines are fairly similar, what is said about the larger machine can be easily applied to the smaller one.

4.1 Melting and Storage System

As mentioned before, a majority of this part of the machine was bought from vendors and assembled. The melting tank itself was purchased from the RITE-HETE™ corporation located in Minneapolis, Minnesota. They specializes in manufacturing melting tanks for solders and other low melting temperature materials. A heated exit nozzle already existed on the tank, a feature that was very important when choosing the tank. This allowed us to connect the tank to the delivery system by simply installing the correct

Figure 4.1 Picture of the melting/storage tank.

Photograph courtesy of RITEHETE Corp.

length of hosing and the proper fittings. An A/C motor is installed on top of the tank and an impeller is placed on its shaft to agitate the alloy and ensure that it remains in solution and at a fairly uniform temperature. Controlled by a thermostat, the motor can be programmed to start agitating when the encapsulator has reached a set temperature above its melting temperature. The tank has its own heating elements and independent temperature controller. The tank is rated to have a maximum temperature 350°F and a capacity of 12 quarts. It has a power rating of 1200W, feeding from a 110VAC voltage source. Through simple heat transfer analysis, we have estimated that it should take approximately 1 hours for the tank to completely liquefy a full tank of alloy, from a cold start. This has been confirmed through use.

Maintenance on the storage take is relatively simple. Droz builds up at the top surface of the liquid encapsulator and must be skimmed of. It is important that the liquid level never drop below the exit nozzle to prevent the droz from getting sucked into the delivery system, thus clogging the injection cylinder and hoses. The tank is refill by simply dropping ingots of solid encapsulation alloy into the bath. However, this has the effect of lowering the temperature of the entire bath and can disrupt the encapsulation process. If too many ingots are placed into the both at once the entire bath will freeze and render the system inoperable until it can be re-melted. Thus, it is sometimes wiser to add liquid encapsulator to the tank bath. The tank can be easily purged by disconnecting the exit nozzle from the injection system and allowing its liquefied contents to flow out.

The cost for the entire unit is approximately $2,000, with the tank being $1,200. It has proved to be very well suited for our application.

4.2 Injection Machine and Delivery System

To deliver the molten encapsulator at an elevated pressure, a pneumatic injection system, comprised of a piston pump, a pneumatic piston, a heater and thermocouples, has been designed. It is able to inject the encapsulator in its liquid state at temperatures as high as 500 F, at pressures as high as 250 psi, delivering a volume up to 75 cubic inches. This injection machine differs greatly from conventional plastic injection machines in that it delivers the material at much lower pressures but in much greater volume. The injection cylinder is made of a stainless steel 303 alloy to protect against corrosion and wear.

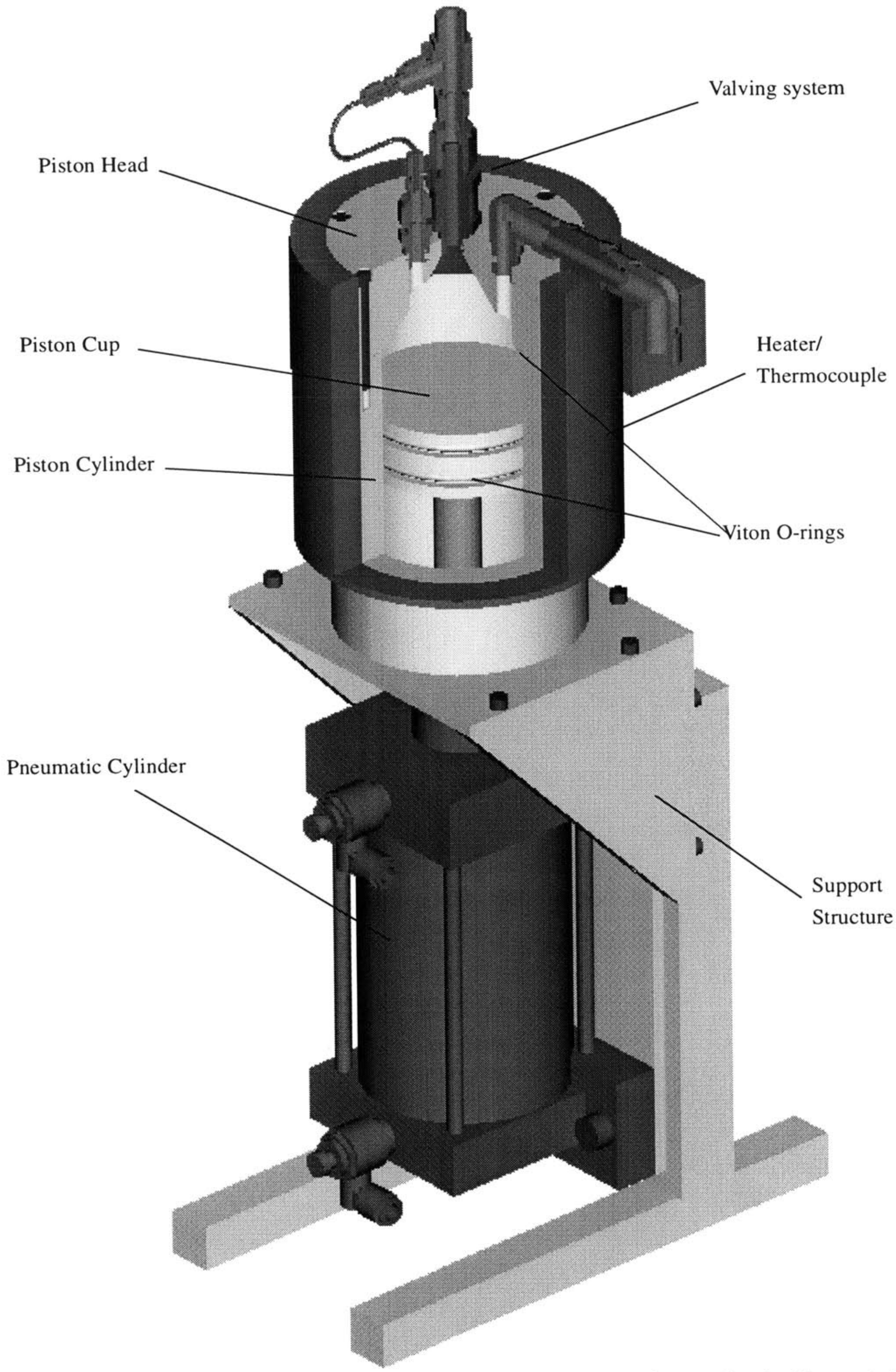


Figure 4.2 Cut away view shows the injection piston, including piston pump, heater, o-rings, valving, pneumatic piston and support structure.

The entire system, with the exception of the pneumatic actuator, is maintained at temperatures higher than the melting point of the encapsulator, using a 1320 watt ceramic band heater with a 120VAC power source.

In manufacturing the injection parts--the cylinder, head, and cup--were all machined on the lathe. The diametric clearance between the cup and the cylinder was specified to be no more than 0.006" and no less than 0.002". The percentage of squeeze the two piston cup o-rings are subjected to is about 10%, as recommended by the manufacturer. A third o-ring is place between the cylinder and the piston head to ensure a good seal. As recommended by the manufacturer, there is about a 25% squeeze. The internal surface finish on the piston cylinder was specified to be no more than 16rms. Thus, some light sanding was required after being lathed.

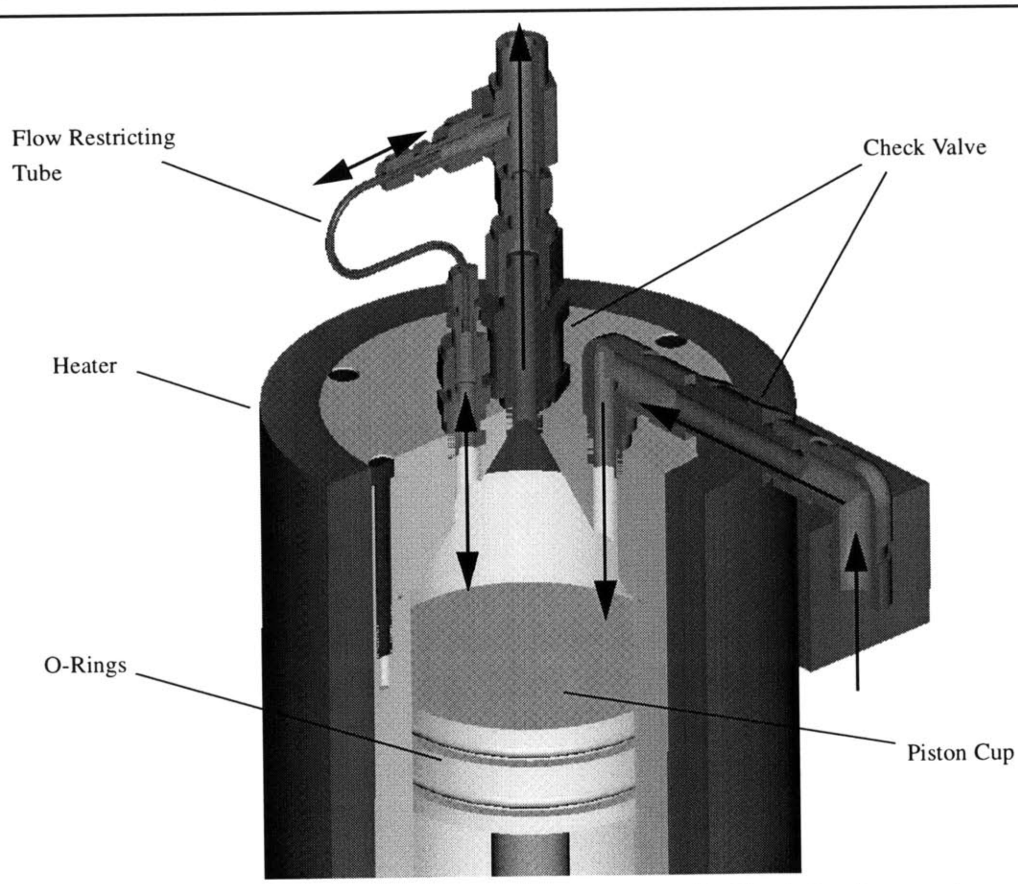


Figure 4.3 Illustration of the flow pattern in the injection system

The injection flow pattern is fairly novel. There are two check valves that restrict the flow of the encapsulator to travel only in one direction-from the melting tank, to the injection piston and then to the clamping system and mold. There is also a third line that allows back flow from the mold to the injection cylinder. This allows the pressure within the mold to equalize to atmospheric conditions once the cylinder is contracted. Thus, when the mold is opened, the encapsulator, under no pressure, will not spill over the injection gates. The diameter of the third line is relatively small compared to the other lines. This restricts the flow to allow just enough of the encapsulator to flow back into the cylinder to equalize the pressure but not to create voids or vacuums in the clamping system and injection lines. The diameter of the third line can be easily changed to accommodate a variety of injection conditions.

4.3 Clamping System

The clamping device has a multifunctional role in the encapsulation process. Its primary purpose is to receive the molds and ensure that the molds remain sealed during the injection procedures. To perform this task, the clamping device has two stages, both pneumatically actuated. However, while a pneumatic piston directly actuates the secondary stage, the primary stage is coupled to the actuator through two sets of linkages. Directly driven, the pneumatic cylinders would only produce a clamping force of less than 1000 lbs, given a supply pneumatic pressure of 75 psi. Since we would like to avoid using hydraulics but still need higher clamping forces than that offer by pneumatics alone, a mechanical linkage is used to increase the clamping force. At the height of its travel, the primary stage can produce about 7000 lbs of force given an air supply of 75psi. Such

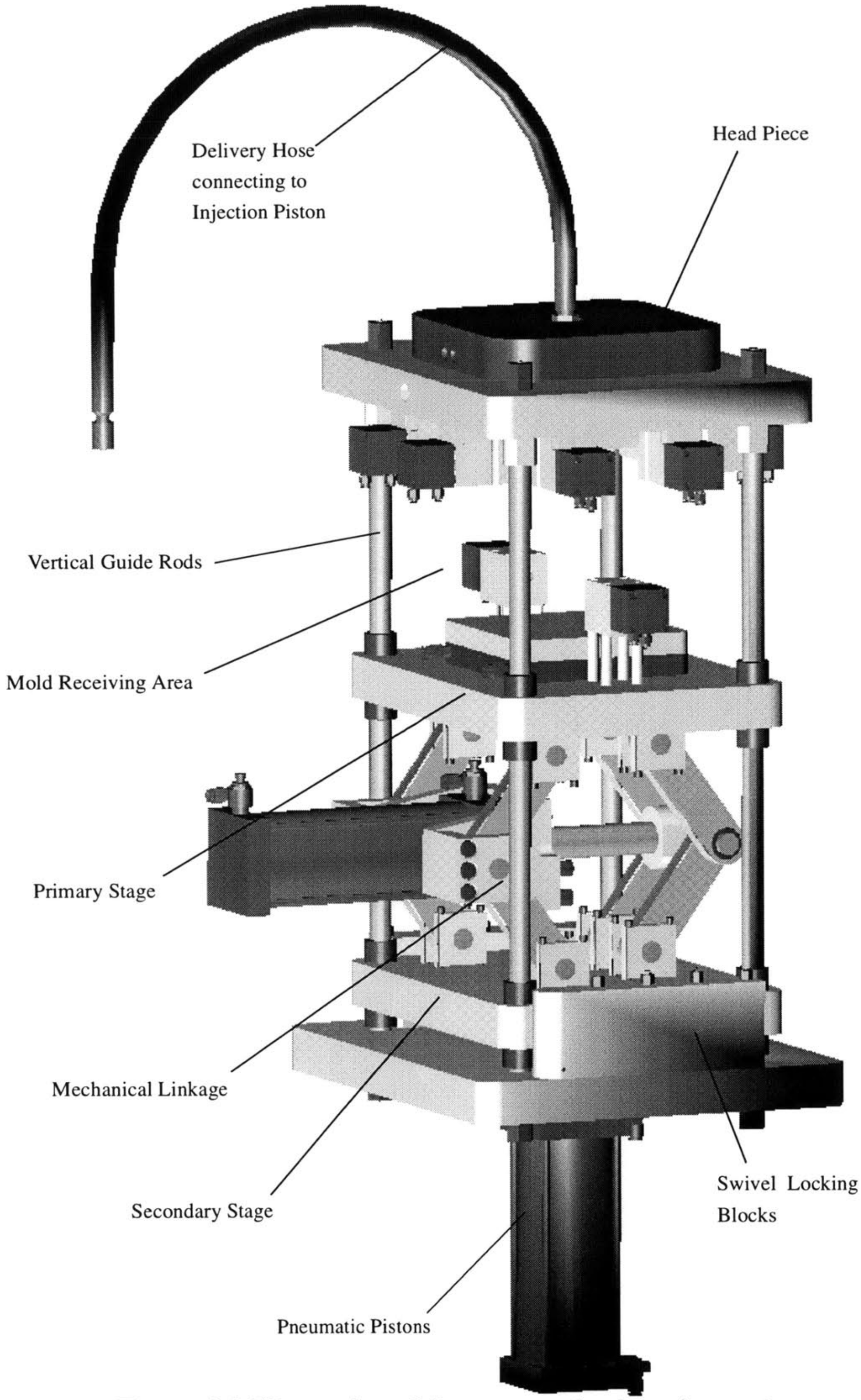


Figure 4.4 Illustration of the pneumatic clamping system

would be amble to seal an 8-inch mold.

The purpose of the secondary stage is to allow the clamping system to receive molds of different sizes and purposes, i.e. 1", 2" or 6" molds and 2-D, 2 1/2D or 3D molds. A pneumatic piston drives this stage to the proper location, after which, locking blocks are swung into place, underneath the stage, to support the clamping loads. Since the sizes of molds are pre-determined, the locking blocks have steps that are designed specifically suited for each mold size and type.

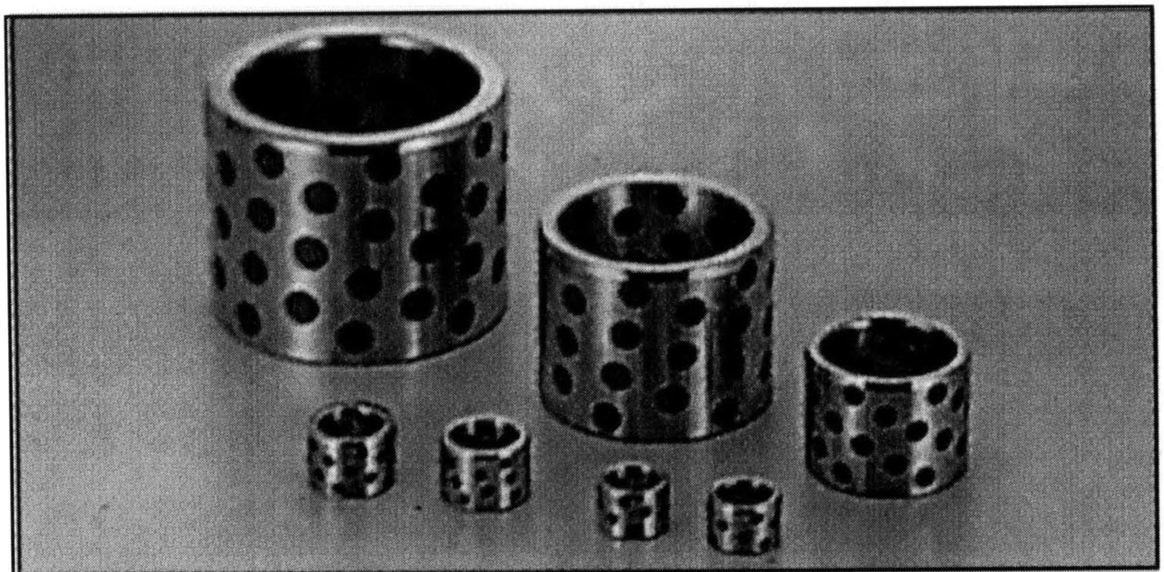


Photo courtesy of Lubo Industry

Figure 4.5 Picture of the sliding element linear and rotary bearings provided by Lubo Industries

Both the primary and the secondary stages travel on the same four vertical guide rods. Purchased from Thomson Industries, Inc., the guide rods are 1" in diameter and provide approximately 30 inches of travel. They are made of 440C steel case hardened to rockwell 50C. The surface finish is 8 Ra and they run straight to within 0.001" per foot. The bearings used to ride on these rods are purchased from Lubo Industries. Lubo's 500 series, self lubricating, manganese bronze sliding element bearings with graphite plugs are installed in the primary and secondary stages and also in the primary stage actuator linkages. These bearings prove to be well suited for our application where the loads are high but the travel velocity is relatively low. These bearings were chosen over rolling element bearings because they can tolerate more misalignment and asymmetric loading. Roller element bearings, with their small ball bearings, have a tendency to jam especially when the bearing spacing to bearing length ratio, the L/D ratio, is large. In our case, the L/D ratio is 4, which exceeds the recommended limit of most rolling element bearing manufacturers. Under ideal condition, these manufacturers recommend a L/D ratio of no greater than 3 [Slocum 92]. Lubo's sliding element bearing seem to have to problem with the large L/D ratio.

The second function of the clamping device is to aid in the delivery of the encapsulation material. Within the clamping device, located directly above the molds, there is a chamber we call the encapsulation reservoir. The reservoir holds the next shot of the encapsulator, and thus, its temperature must be monitored and controlled carefully. To do so, heaters are placed in specific location so as to achieve a uniform and efficient heating. One is place above the encapsulation reservoir and a second is placed underneath the molds so as to be able to preheat the molds before injection. Thermocouples are placed in each of these heating zones as well as on the mold and at the injection gates to determine the state of the encapsulation material and observe the overall progress of the injection cycle. A valve is placed underneath the encapsulator reservoir to cut off the flow of the encapsulator when the mold is in its open position. The valve is operated by a pneumatic piston. There are also auxiliary clamping wedges used to keep the mold pieces in place and to allow users to quickly switch molds without having to shutdown the injection sys

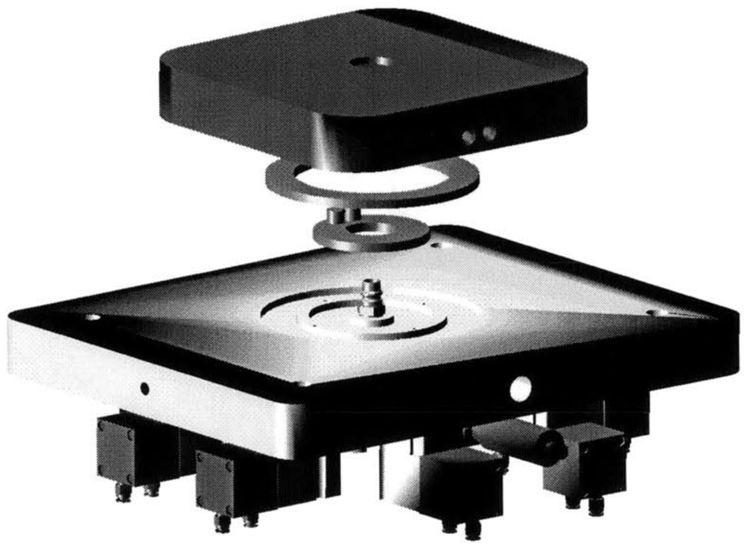


Figure 4.6 Top view of the head piece unit
Visible are the 2 ring heaters used to change the temperature of the reservoir and the insulating cover above it

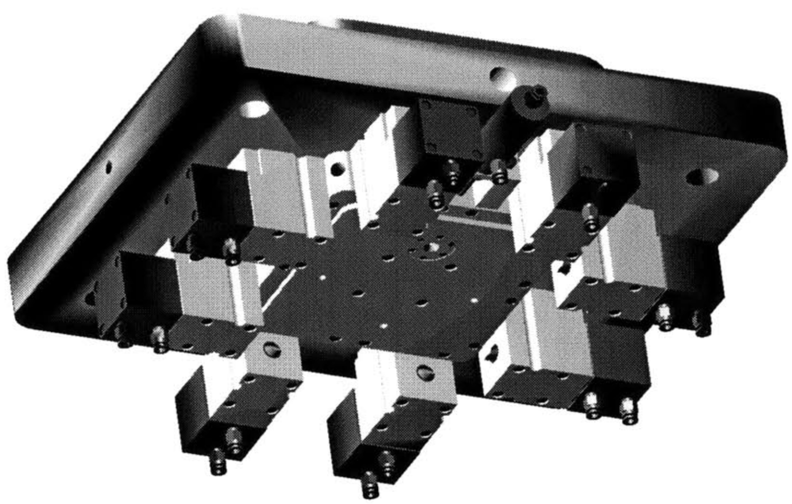


Figure 4.7 Bottom view of the head piece unit
Visible are the wedge clamp units used to hold the mold gate plate in place and to allow quick change over to a different gate plate

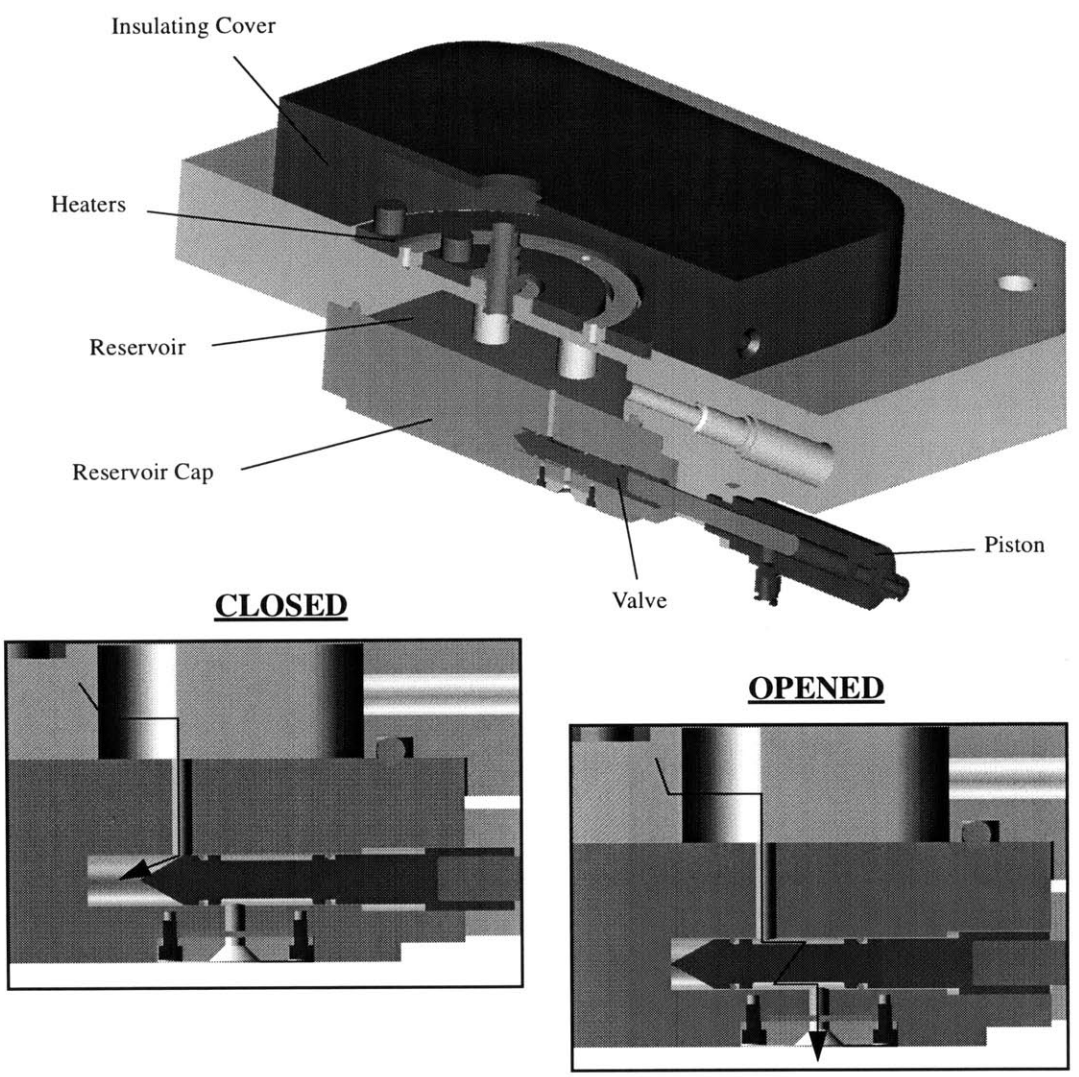


Figure 4.8 Illustration of the valve within the head piece

tem and allow it to cool.

Minimizing molding cycle time is extremely important. The most significant factor is the heating and cooling of the molds. Thus, it is vital that we thermally isolate the mold from the rest of he heated zones of the clamp, specifically, the encapsulator reservoir. To do this the injection gates are manufactured out of a high temperature plastic, Ultem™. The Ultem™ allows for rapid cooling of the molds while minimizing heat loss from the

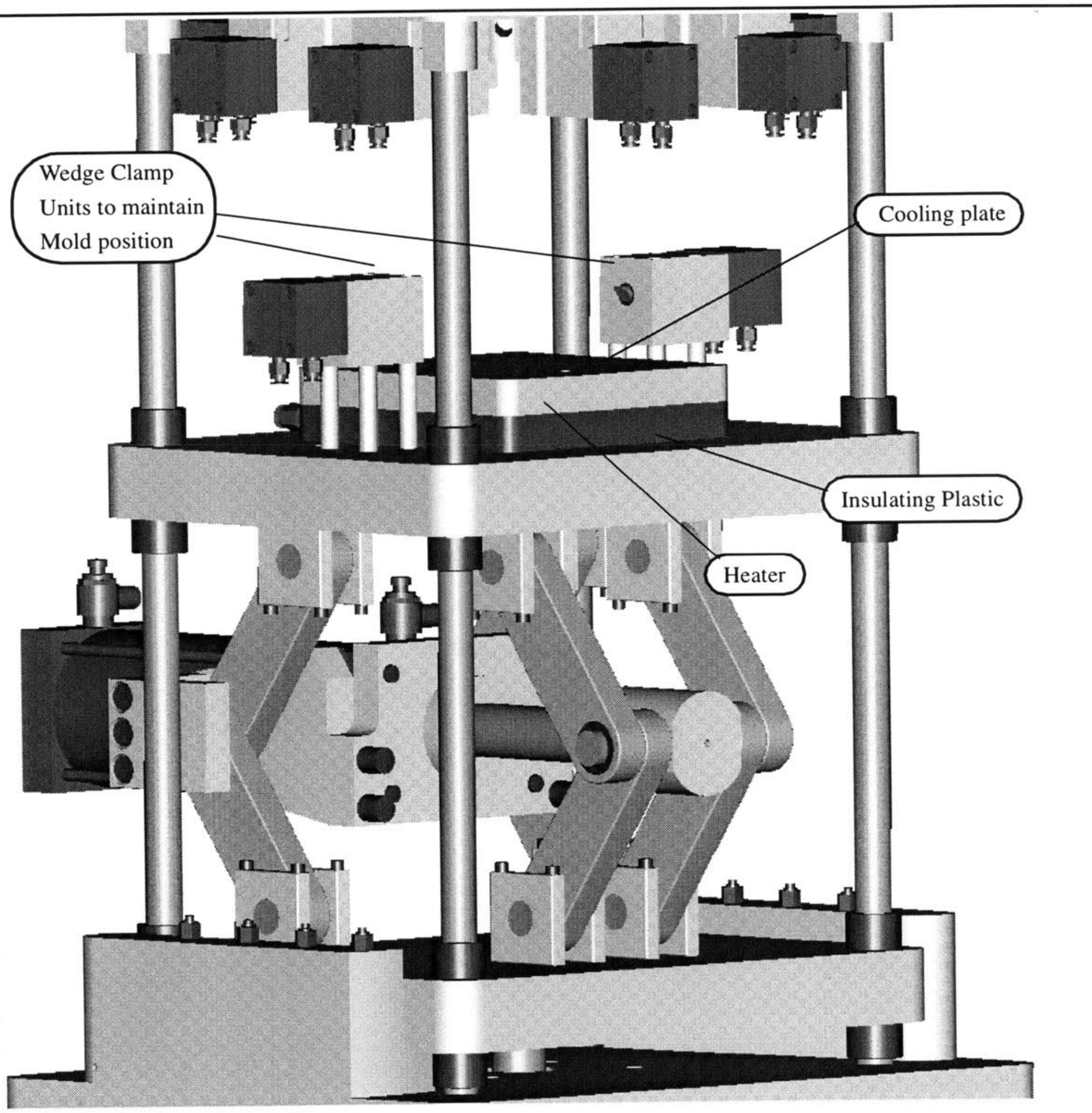


Figure 4.9 Illustration of the mold receiving area of the clamping system

reservoir and the rest of the clamping system. A cooling plate is located beneath the mold between the mold and the mold heating source. It circulates air at high velocity using the pneumatic air supply as a pressure source. Another layer of insulation is placed beneath the mold heaters to isolate it from the rest of the clamping device. Thus, the mold is sandwiched between the two layers of insulation so that it may be cooled to a temperature just below the melting point of the encapsulator without disrupting the thermal states of the rest of the machine.

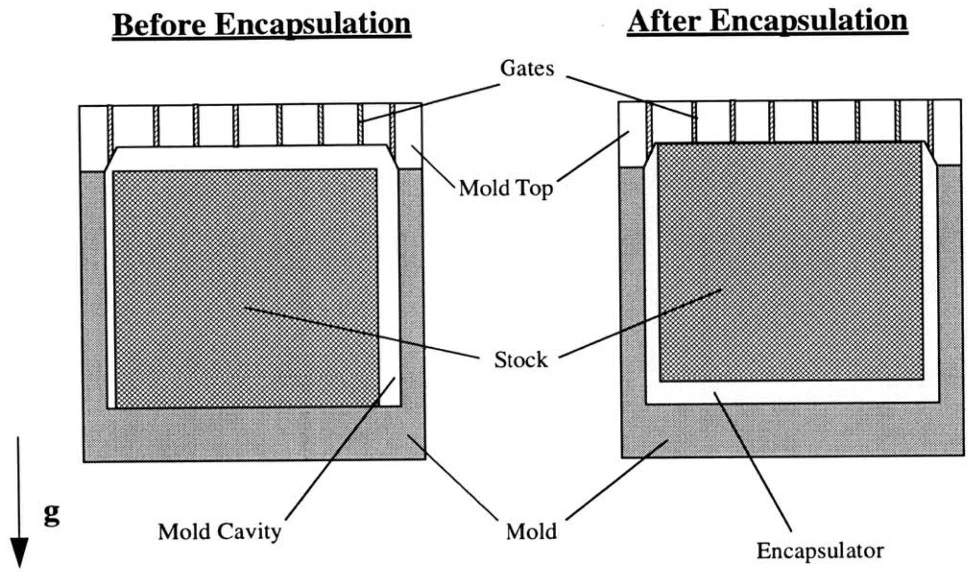


Figure 4.10 Illustrations of the importance of machine orientation
Before encapsulation, the stock is off center. Afterwards, buoyancy forces have pushed the stock up, centered it within the mold, and left the top face exposed.

The orientation of the clamping system is also very significant. The objective of the encapsulation is to only form five of the six sides of a cube since the sixth side should be left exposed so that machining can be done to that side immediately without having to machine away the encapsulator. Therefore, to facilitate this, the clamp is positioned upright and vertical. Since the encapsulator is usually denser than most machined materials, we can expect the block to float to the top of the mold. By positioning the clamp in this way, we can automatically, and with great ease, mold around five of the six sides of the rough-cut stock. The top side, the side that floats up and mates with the top wall of the mold, is left exposed and available to be machined immediately. To be extra clever, we can chaffer the top side of the mold so that the block will automatically center itself as it floats up.

4.4 Molds

A set of molds has been developed so to be able to mold 1, 4 and 6 inch stock and form those encapsulation blocks whose walls are perpendicular to its adjacent walls to within 0.0005 inches. The accuracy requirements are extremely tight. Therefore, the molds are precision ground, and, in many cases, a wire EDM machine is used to machine the actual mold cavity. The accuracy requirement is another reason why the molds are filled under pressure. Otherwise, air pockets and wetting problems between the encapsulator and the mold would prevent the encapsulator from fully filling the molds. However, under these high pressures, sealing the molds becomes more difficult. The viscosity of the encapsulator is similar to that of water, and thus it flows very readily even through small cracks.

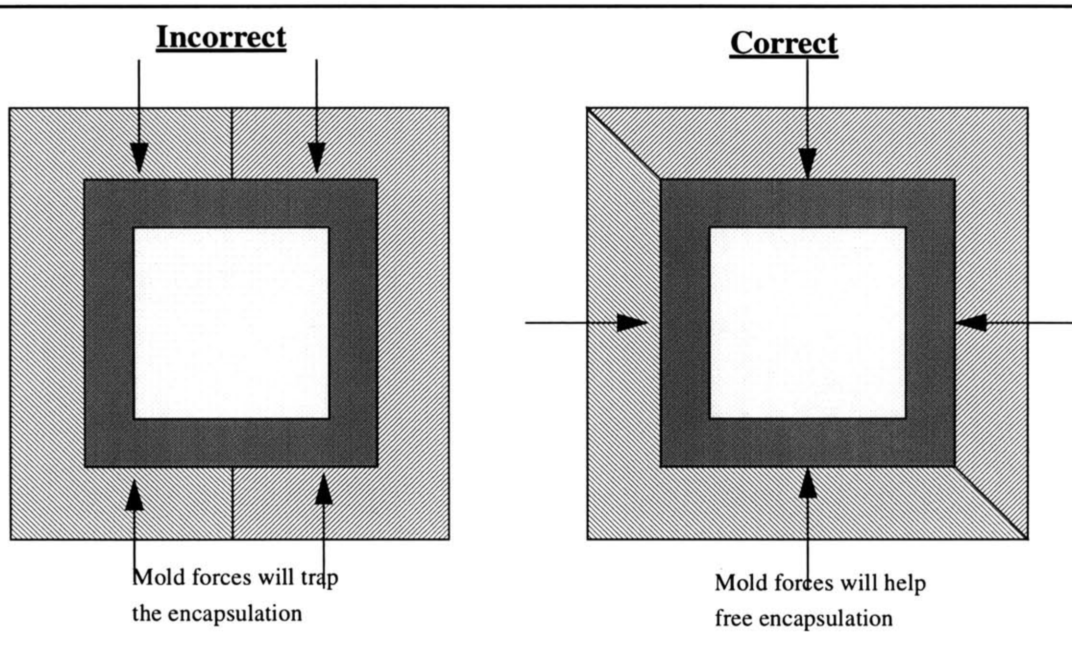


Figure 4.11 Illustration of the correct mold parting line placement

Sealing the molds using simple rubber o-rings is usually not viable since there exist multiple parting lines that intersect each other in each mold. Thus, all mating surfaces must be ground flat and polished to a surface finish of less than 8 rms. Parting lines need to bisect the block diagonally because the pressure at which the encapsulator is injected into the mold will tend to make the block rub against the mold walls. Any other parting direction would result in the encapsulation assembly becoming jammed inside the mold and irremovable

4.4.1 3-D Molds

The 3-D mold is composed of 4 pieces. Assembled together, these four pieces create a cubic mold cavity in which the encapsulation of the rough-cut stock occurs. The pieces can described as two plates that sandwiches two "L" shaped pieces. In the bottom plate a single square pocket is machined. Its dimensions are that of the finished cube and its depth is the thickness of the encapsulation layer that surrounds the stock. To ensure that the two "L" pieces mate to each other repeatably, kinematic balls and V-grooves are manufactured onto the mating surfaces. In order to maintain a high tolerance in the mold cavity, the two "L"s are mated together and machined as one piece using wire EDM. This assures that the mold walls are perfectly vertical and that the parting line exactly bisects the cube diagonally. The top plate also contains injection gates through which the encapsulator is delivered into the mold. A chaffered pocket is machined into the top plate to allow the block to center itself as it floats upward. Also, 8 wedge features are machined into the sides of the top plate so that they will mate with the wedge clamp features of the clamping system. This allows the plate to be installed and removed from the clamping system easily and quickly.

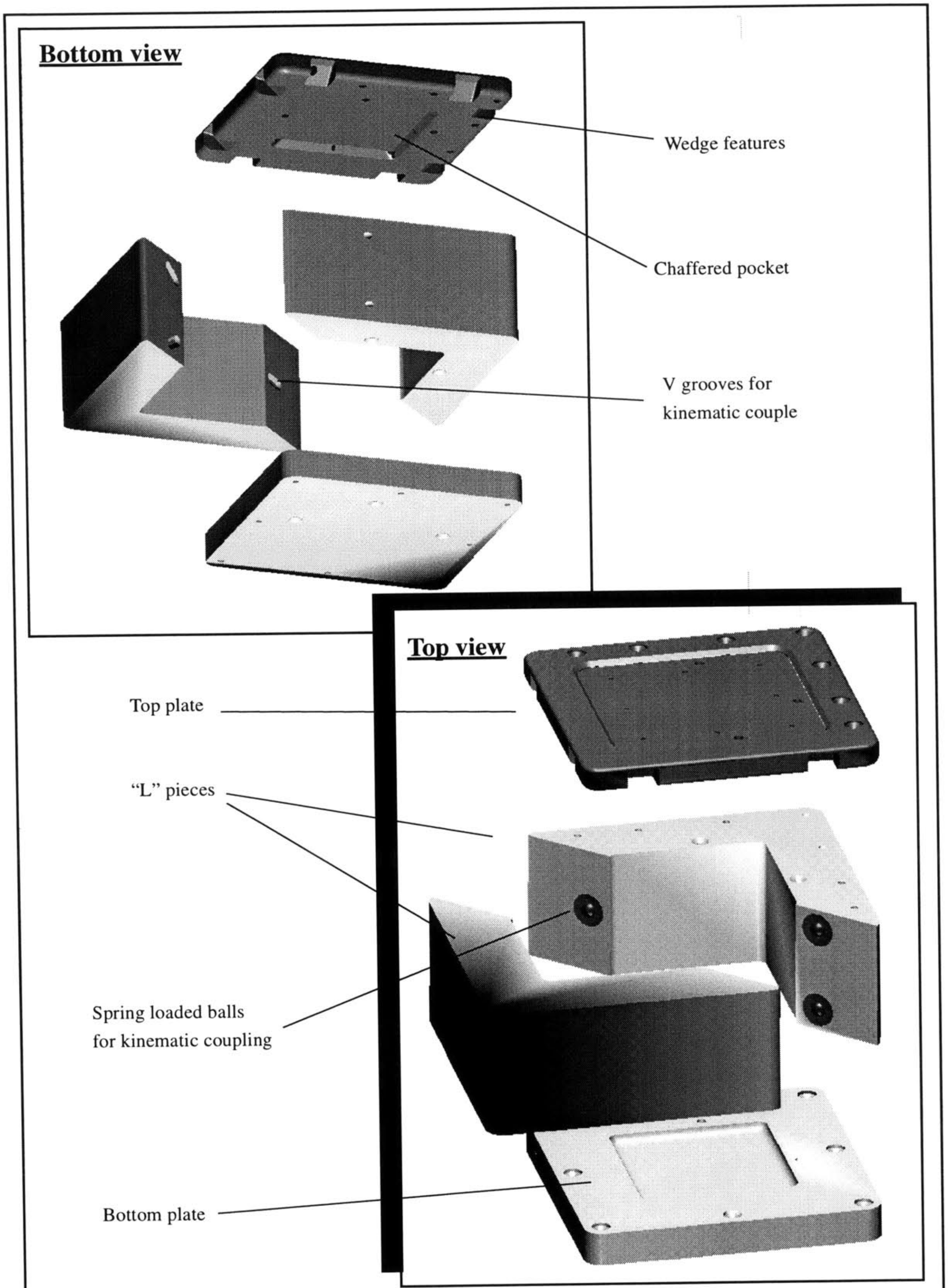


Figure 4.12 Illustration of the 3-D mold assembly

The top plate and the "L" shaped pieces that form the walls of the mold are aligned though 3 dowel pin holes and attached through screws. The two "L" piece themselves are joined together with 2 sets of bolts.

The bottom plate is aligned to the rest of the mold using the similar dowel pin method as used above. However, they are not physically attached to the rest of the mold. When installed into the clamping machine, the top plate and the "L" pieces are attached to the top potion, onto the reservoir cap. The bottom plate is allowed to rest on the primary clamping stage, place directly above the mold heating and cooling plates.

4.4.2 2-D Mold

The 2-D mold consists of 3 pieces, the gate plate, the fixture/mold frame, and the bottom plate. Like gate plate in the 3-D mold, wedge features are machined into the sides of the 2-D gate plate to allows it to be installed quickly and easily onto the clamping system. Because there is no need for a diagonal parting line, all the parting lines of the 2-D mold lie parallel to each other. This allows us to use o-rings to seal the molds. There are 2 o-rings. One is sandwiched between the gate plate and the fixture frame, and the second is sandwiched between the fixture frame and the bottom plate. Because we are using the fixture frame as a fixturing device inside the milling machine, it has 4 bolts holes and 2 dowel pin holes to allow us to bolt and align it on a machine tool bed. The fixture frame also have similar wedge features to allow it to be loaded and removed from the clamping system easily.

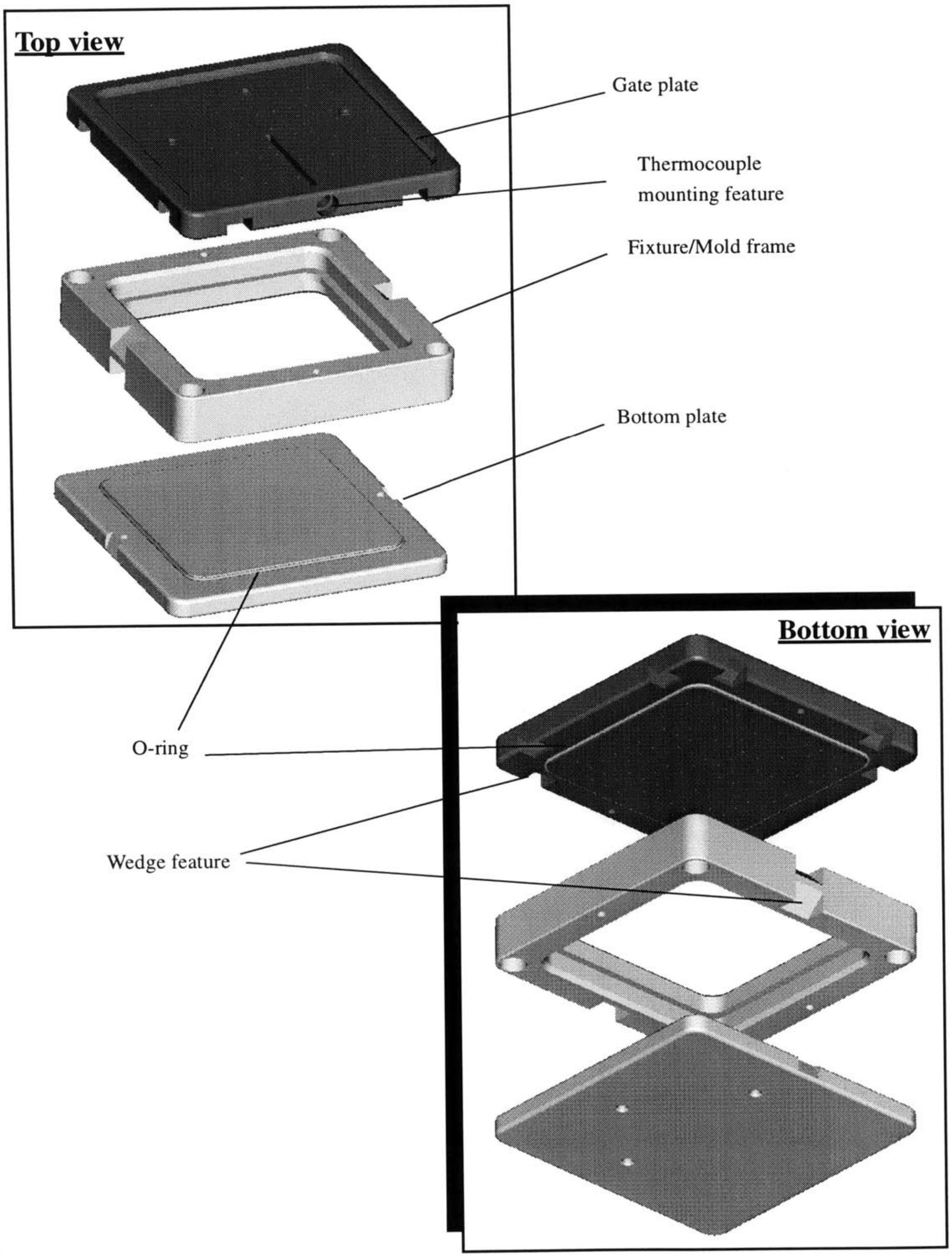


Figure 4.13 Illustration of the 2-D mold assembly

4.5 Portable Encapsulation Machine

The smaller encapsulation machine was design to be portable. The intention was to travel with it to various local machine shops and test the performance of encapsulation fixturing in a typical job shop environment. Job shops should prove to be a ideal setting for preliminary testing since they are in the practice of producing parts in low quantity. Very few fixturing and part handling tasks are automated. Thus, jobs tend to be very labor intensive and parts, very expensive. Our plans are to place the encapsulation machine into this environment and compare the total machine time for parts made using encapsulation fixturing and those without. We have yet to place the encapsulation system into such an environment and perform these tests and comparisons. They are scheduled for this coming summer and their results shall be published in the coming months.

4.5.1 Machine design

The functional requirements for the portable encapsulation machine are identical to those of its bigger brother. The machine can still be dissected into 3 components, the heater/storage tank, the injection system, and the clamping system. It is slightly more difficult to physically distinguish each within the overall machine. Because we have added the additional function of portability, their physical embodiment have been optimized for weight and size. The general approach to accomplishing this task was to minimize the plumbing and to design a single unified support structure to house all three machines. The result is the design shown in Illustration of the portable encapsulation machine.

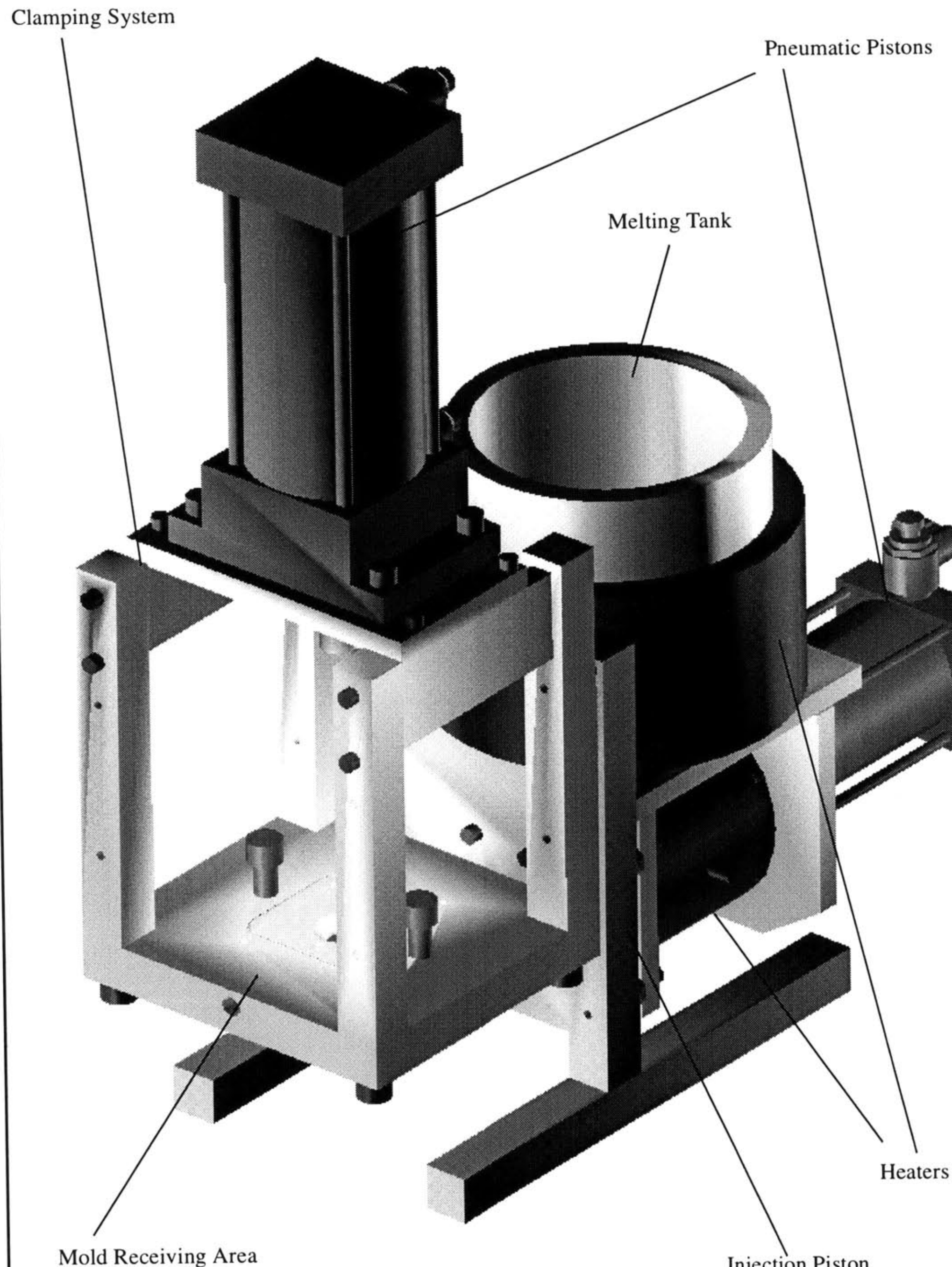


Figure 4.14 Illustration of the portable encapsulation machine

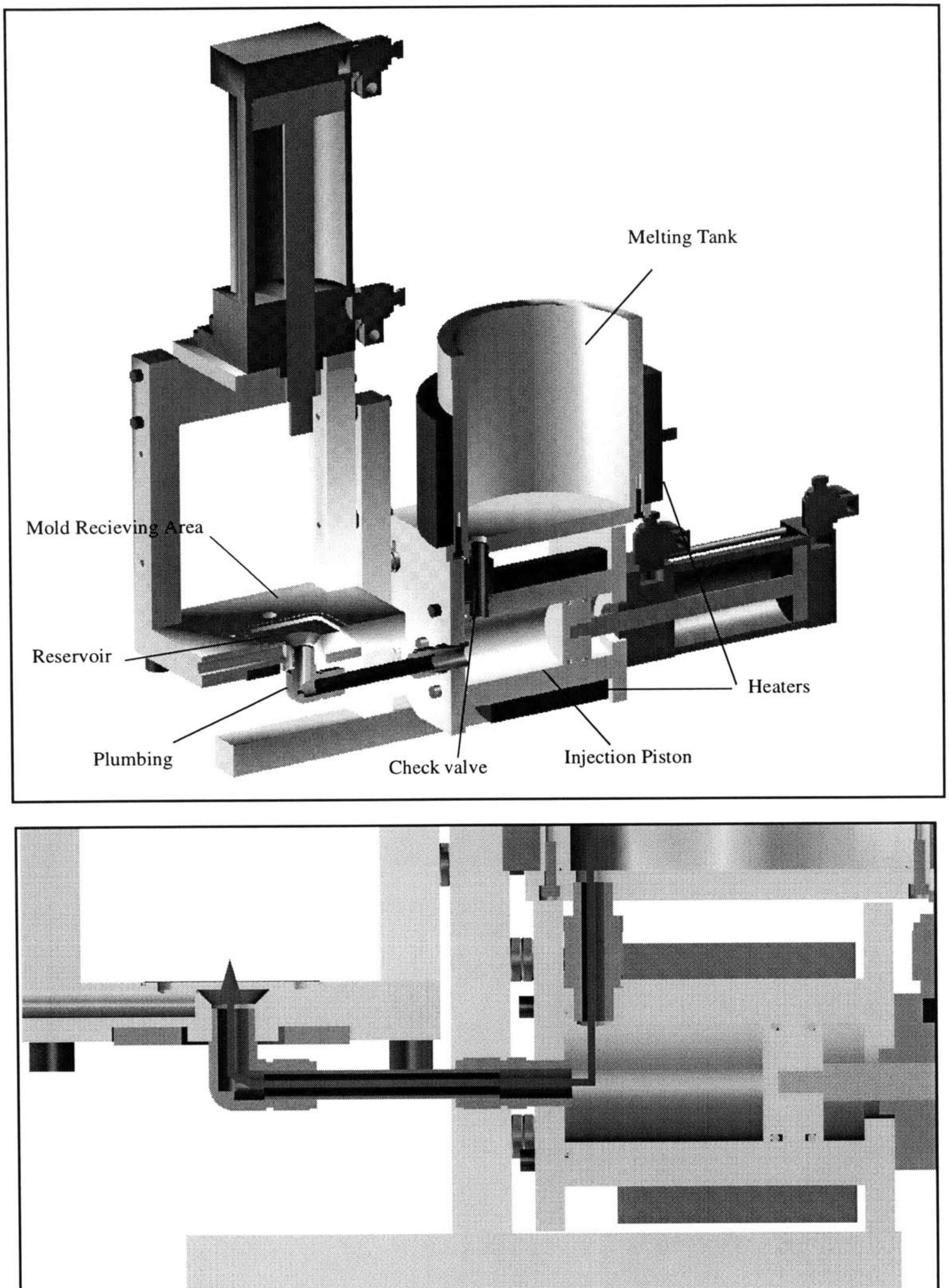


Figure 4.15 Illustration of flow pattern within the portable encapsulation machine

The portable encapsulation machine was design to fit inside the trunk of a compact car and be transported by a single human being. Thus, the size was limited to 30" x 15" x 24" and the weight, to 75lbs, the maximum dimensions and load a human being can carry comfortably for a short period of time.

Because of the size limitation, the maximum mold size the encapsulation machine can receive is 2". It can deliver approximately 1000lbs of clamping force for a 85psi pressure source. Similar to the larger machine, the maximum injection pressure is 250 psi. There are 4 heating zones in the machine. Those include the tank, the injection piston, the plumbing, and the mold receiving area. The maximum temperature in each zone is 450°F. The totally power needed by the portable machine is 1800Watts, supplied by a 120VAC source. In choosing the heaters for the system, we were careful not to draw more than 20amps. Since normal 120VAC wall sockets are fused at 20amps, only one socket would be necessary to supply the 1800 watts needed to power the machine. The warmup time was decreased from 1 hour in the larger machine to approximately 30 minutes in this smaller one in order to allow users to quickly setup the equipment upon enter a new facility.

4.5.2 Design Changes in Portable Encapsulation Machines

There are only two major differences between the smaller and larger machines. The first is the flow pattern. While the larger machines has two check valves and a third pathway to allow back flow, the smaller machine has only one check valve, between the tank and the injection piston. The plumbing between the injection piston and the clamping system allows bi-directional flow. The check valve is removed to conserve space. Originally, in the larger machine, the check valve was placed between the injection piston and the clamping system to allow the piston to properly draw encapsulation from the tank. Without the valve, the piston has a tendency to draw air from the clamping system. Without the check valve, priming the injection piston would be a tremendous hassle. We avoid this problem in the smaller machine by placing the melting tank directly above the injection piston and allowing gravity to fill and prime the piston when then check valve is manually opened. However, without the check valve, we must ensure that the mold receiving area of the clamping system lie above the injection piston, else the encapsulation will readily flow out under gravity.

The second change is in the clamp orientation. While the clamp still sits upright and vertical, the injection gates now come from the bottom. Previously, they had been place above the molding area to allow the block to float upwards upon injection and center itself and uncover its top face. See section 3-D Molds for more details. We have decided to forego this design element in order to save space and reduce the complexity of the design. By placing the reservoir below the molding area we no longer have to include a valving system to prevent leakage. The encapsulator will remain in the resevoir as long as the machine remains upright.

4.5.3 Molds

A 2 1/2D mold has been constructed from the portable encapsulation machine. Made of stainless steel 304 alloy, it can be slid into the molding area and anchored to the clamping system through 2 screws. The sealing is accomplished through conventional Viton™ o-rings. The mold walls are chaffered to 5° to allow easy removal of our encapsulation. Because the tolerances are so loose on this mold, all of the parts can be easily manufactured in a 3 axis milling machine. The taper is machined in using a 5° tapered endmill.

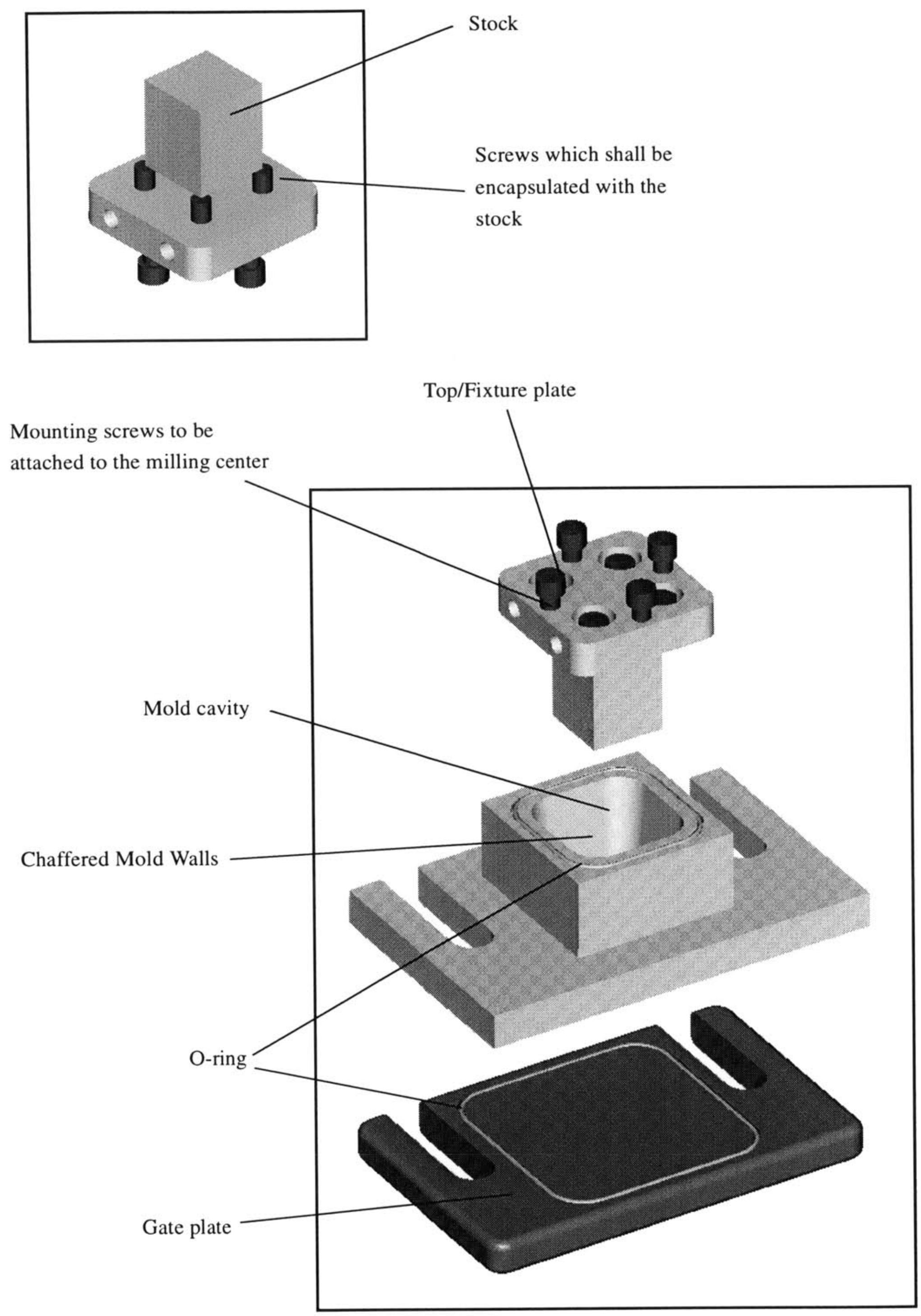


Figure 4.16 Illustration of the 2 1/2 D mold for the compact encapsulation machine

Chapter 5: Work In Progress

Thus far, we have concentrated on describing the development of an encapsulation machine. However, our ultimate goal is the creation of an universal automated fixturing system, of which the encapsulation machine will subsystem. We have focused on the problems and hurdles faced in designing and manufacturing the encapsulation machine, and have presented the best solutions, in terms of performance and economic issues. In this section however, we shall discuss other major developments and important pieces of the automated universal fixturing systems. We will discuss possible refinements of the encapsulation technique, and introduce machines, still in their conceptual design stage, that are intended to improve the automation and cycle time of the overall fixturing system.

5.1 Fixturing System

Once a workpiece has been encapsulated, fixturing it within a machine tool becomes trivial. However, this is certainly not to say that one should not pay attention to the design or selection of the fixturing/workholding device that must be installed in a machine tool. Buying an ordinary vise may suffice in some simple cases. However, to truly take advantage of what encapsulation fixturing has to offer, the ability to fully automate fixturing, we need to give serious thought to our fixturing requirements for an encapsulated workpiece and how best we can fulfill these requirements.

In a conventional, off-the-shelf two-walled vise, linear motion is directly constrained in only one direction, in the other two directions, the workpiece is immobilized using frictious forces between the vise and workpiece. A workpiece held by a two-walled vise must always be relocated once removed from the setup, since no hard stops exist to fix the workpiece's location in all three directions. Thus it would be a great improvement to add stiffness to the workholding device and remove the need to relocate the workpiece once removed from the fixture, especially since encapsulation fixturing depends on having repeatable multiple setups.

The workholding device proposed will have four walls, each orthogonal to its adjacent. Thus, there will be direct constraints to prevent motion in the entire horizontal plane. Motion in the vertical plane will still be constrained through frictious forces. This should provide sufficient stiffness and support since the upward forces generated in a milling machine are relatively insignificant. Because of the encapsulation must guarantee orthogonality of its walls, being overconstrained in a four walled vise will not prove to be a tremendous ailment in terms of accuracy and repeatability.

The vise will also be equipped with nozzles from which jets of a liquid and gas can be emitted to fully clean and clear the vise of machined chips and debris. The vise will also be equipped with a compact linear measuring devices, a piezoelectric device or a capacitive sensor, so as to able to measure the block size and automatically locate the workpiece's center and offset the machine tool to the proper position.

In the four-walled vise system, two adjacent walls will be fixed to ground and immovable. The other two will be actuated to clamp the encapsulation blocks. However, unlike two-walled vises, which needs to accommodate a wide range of workpiece sizes, the four-walled vise will be designed only to fixture one size. Since encapsulated blocks will only be produced in discrete sizes, there is no need to build a variable vise. Thus the actual

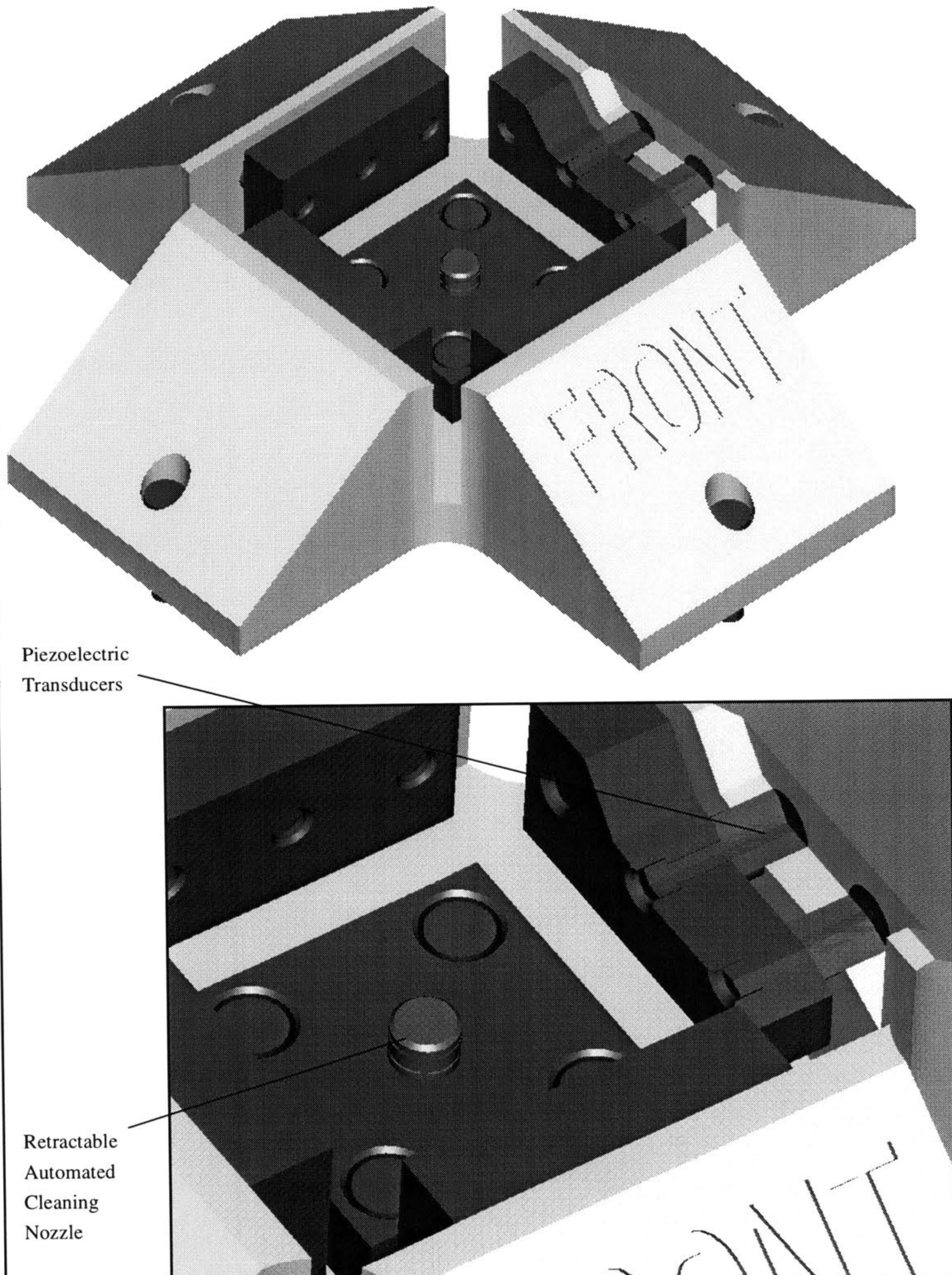


Figure 5.1 Conceptual Isometric drawing of the four-walled fixturing device

travel of the vise walls need only be on the order of 0.01 inches, enough to account for the variations in the dimensions of a set block size and allow enough clearance for easy placement and removal of the encapsulation block. Thus, one possibility for actuators would be to use the same piezoelectric transducers to not only measure the block sizes but also actuate the vise walls. The cost, performance and suitability of using piezoelectric transducers is still being investigated.

With this device in the machining center, an operator no longer has to manually offset to the correct center or find the edge of a workpiece. This reduces setup time and the possibility of operator error. The self cleaning functions allows the operator to load in new blocks immediately without having to stop and thoroughly clean and clear the vise of chips and debris. The vise becomes an integrated part of the milling center communicating with it and operating with it cooperatively.

5.2 Ultrasonic Soldering

In laboratory experiments, the encapsulating materials used have generally been fusible alloys, such as the eutectic solder 58Bi-42Sn, and the stock, because of the ease by which they can be machined and their popularity in industry, has been engineering metals such as 6061-T6 aluminum and 300 series stainless steels. Unfortunately, a tenacious oxide layer that naturally exists on most metallic alloys prevents wetting between the encapsulator and the stock. As a result, the encapsulation assembly is only held together by mechanical interlockings at the macroscopic level and in some cases by frictious forces that result from the contraction of the encapsulator around the stock. When a majority of a part's geometry is convex, macroscopic mechanical interlockings and frictious forces are no longer sufficient to support and immobilize the workpiece within. In these cases, metallurgical bonding and microscopic mechanical interlocking are the only two possibilities that allow encapsulation to perform its fixturing functions properly. There are a number of ways to induce adhesive bonding between solders and aluminum. Fluxing is the obvious solution, widely use in industry. However, fluxing makes the encapsulation process more cumbersome. Automatic application and removal of fluxes require additional machinery, increasing capital and maintenance costs. Also, in an enclosed mold, fluxes have nowhere to run off. It would build up on the molded surfaces, destroying the surface finish on the molding and the quality of the fixturing system as a whole. Pickling, anodization, or sand-blasting the aluminum surface to remove the oxide layer and to create microscopic ten-drils, cracks and crevices are other possibilities. While these three are less intrusive than fluxing, the reliability of these bonds is still questionable. The high surface tension of the encapsulator and the return of the oxide layer immediately upon contact with an oxygen atmosphere makes wetting into the tiny crevices unlikely without a very high pressure source.

The most viable solution to this problem can be found in research that dates back to the 60's, when the academia and industry were searching for new processes that would allow the manufacturing of all aluminum heat exchanger.

5.2.1 Background-All Aluminum Heat Exchangers:

In the late 60's, interest in ultrasonic soldering grew with the conception that an all aluminum heat exchangers for refrigeration and air conditioning systems could be constructed fluxlessly using new technology. The impediment for making an all-aluminum heat exchanger was in the soldering of the return elbow to the bell shaped sockets of the cross-flow tube, as shown in Photograph of return elbows for all-Aluminum heat exchangers. Previously, the tube assembly was made of copper, which could be reliably and easily flux soldered. Switching to aluminum, though it would produce cost saving because of the cheaper material price, would add complexity to the assembly process with the need to use stronger fluxes and more expensive cleaning and water treatment equipment. The progression into ultrasonic soldering was logical. Ultrasonics eliminated the need for fluxing and had already been proven to work well with aluminum in the late 30's.

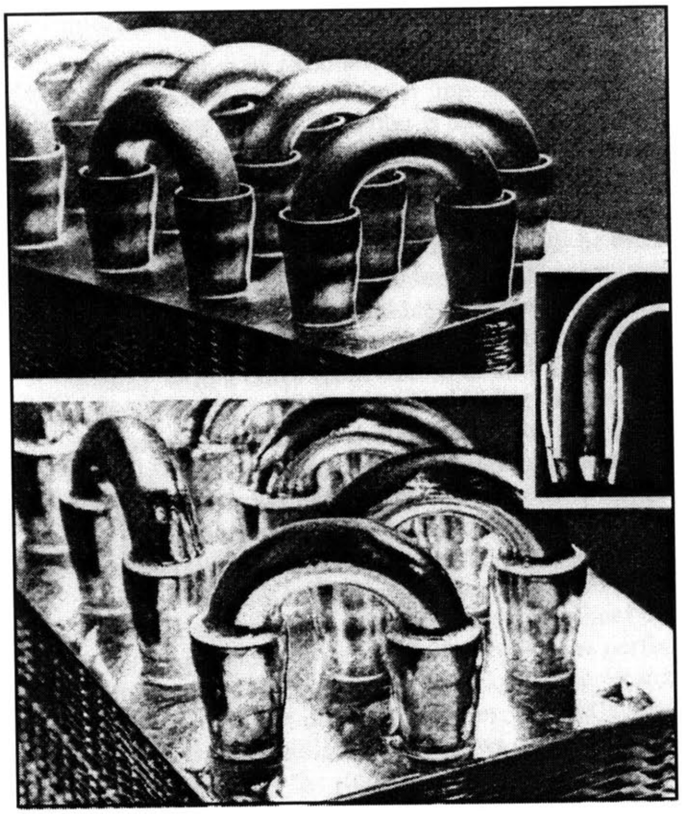
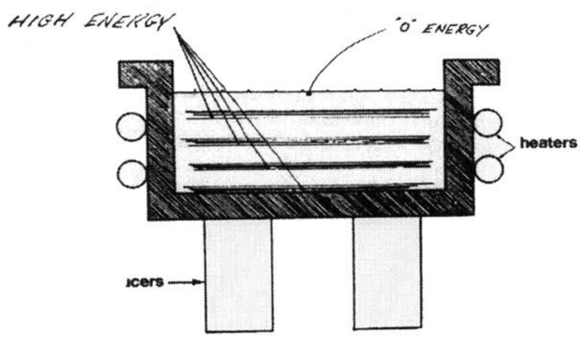
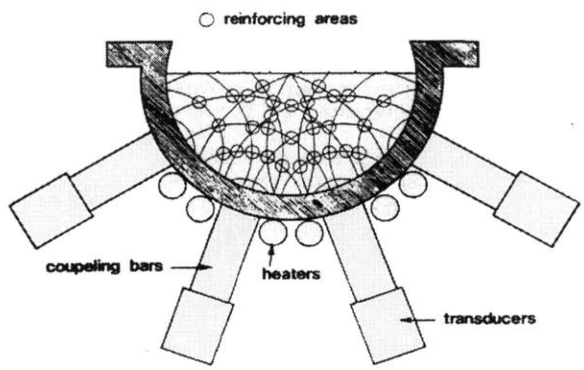


Figure 5.2 Photograph of return elbows for all-Aluminum heat exchangers

The Alcoa 571 process, or the immersion method, was developed to ultrasonically solder the return bend to the bell socket in heat exchangers. The Alcoa 571 process entailed preheating the bend and socket, and immersing the elbow and tube, already pressed fit together, into a heated tank of molten solder. Ultrasonic transducers, mounted onto the



— *Rectangular solder tank showing the high and low ultrasonic energy level distribution*



– *Round-bottom solder tank showing locations of reinforced energy levels*

Figure 5.3 Illustration of the two types of ultrasonic soldering tanks developed for soldering the return elbows of all-aluminum heat exchang-

outside walls of the heated tank, were activated for a period of time usually less than 5 seconds, at a power level of about 1kW and a frequency of 20kHz. The bath served as the cavitation medium through which the ultrasonic energy could be transmitted to the workpiece to remove the oxide layer. The bath also served to prevent reoxidation and hydrostatic pressure of the bath served to push the solder into the bend/socket joint gap. Because of the lack of capillary flow, the length and quality of the soldered joint relied heavily on the submerged depth. However, the submerged depth was limit by the return elbow size. Thus, high intensity cavitation was desired near the surface of the solder pool.

The first tanks developed had a rectangular shape with transducers mounted on the bottom. These produced very low cavitation intensity near the solder surface and proved to be difficult to implement in an manufacturing environment. A round bottom tank was adopted soon after. Its shape tended to produce higher cavitation intensity throughout the volume of the tank, especially near the surface [Hunicke 76] [Graff 77]. These tanks were implemented in a few small manufacturing test plant but, despite their success, their use never achieved wide acceptance in industry.

5.2.2 Applications towards Encapsulation Techniques:

Manufacturing all-aluminum heat exchangers using ultrasonic soldering techniques would eventually lose out to conventional soldering methods as copper prices fell and aluminum prices rose. The process' demise would be further aid with the development of better fluxes and cheaper cleaning methods. But most importantly, researchers were unable to transform the ultrasonic method into a mass production soldering system. Its throughput simply could not compare with that of conventional automated gas-flame soldering using preformed insertion rings of a self-fluxing solder.

Fortunately, these drawback do not exist in our encapsulation technique and the progress made by this industry in ultrasonic soldering can be adapted and used to aid in our encapsulation efforts. Much like the immersion process, the ultrasonic application for encapsulation involves pretinning the block stock with a thin coating of the encapsulator. This can be accomplished by immersing the raw cut workpiece, oil, grease free and preheated, into a heated ultrasonic pot much like those used in the heat exchanger industry. Application of the ultrasonics for a few seconds will produce cativation within the solder bath and remove the oxide skin from our aluminum block. Once the oxide has been removed, the surrounding encapsulator will readily wet the walls of our aluminum and produce a uniform solder coat when the workpiece is removed from the ultrasonic tank. The solder coat is allowed to solidify outside the bath and the block is place inside our encapsulation mold. Additional molten encapsulator is injected into the mold chamber. The temperature is maintained above the liquidus of the encapsulation for a few moments, allowing the solder coat to reflow and weld with the new solder. Since no atmosphere comes into contact with the workpiece once in the ultrasonic bath, once the encapsulation coating has reflowed, a clean, oxide free surface is exposed to the new encapsulation shot and a complete and uniform bond can be achieve throughout the entire surface of the block.

Developing an ultrasonic soldering process for our encapsulation application is not without its own set of problems and hurdles. In experiments conducted by Lystrup [Lystrup 76a], solder composition was found to effect cavitation intensity. As in any waveform traveling between two mediums, part of its energy is transmitted and the other part is reflected back. The transmission coefficient is dependent on the material properties, the acoustical impedance of the horn and encapsulator, and to the cavitation intensity experienced by the specimens. The solders used in the heat exchanger applications were predominantly Zinc alloys, 95Zn-5Al in particular, because of their high transmission coefficients. Zinc has a cavitation threshold 1.5 times that of water. Lead is 10 times as high and tin, 20. Thus, by using the Bi-Sn eutectic that we have been developing our encapsulation process for, we can assume that cavitation intensity will decrease, and thus oxide removal will take longer

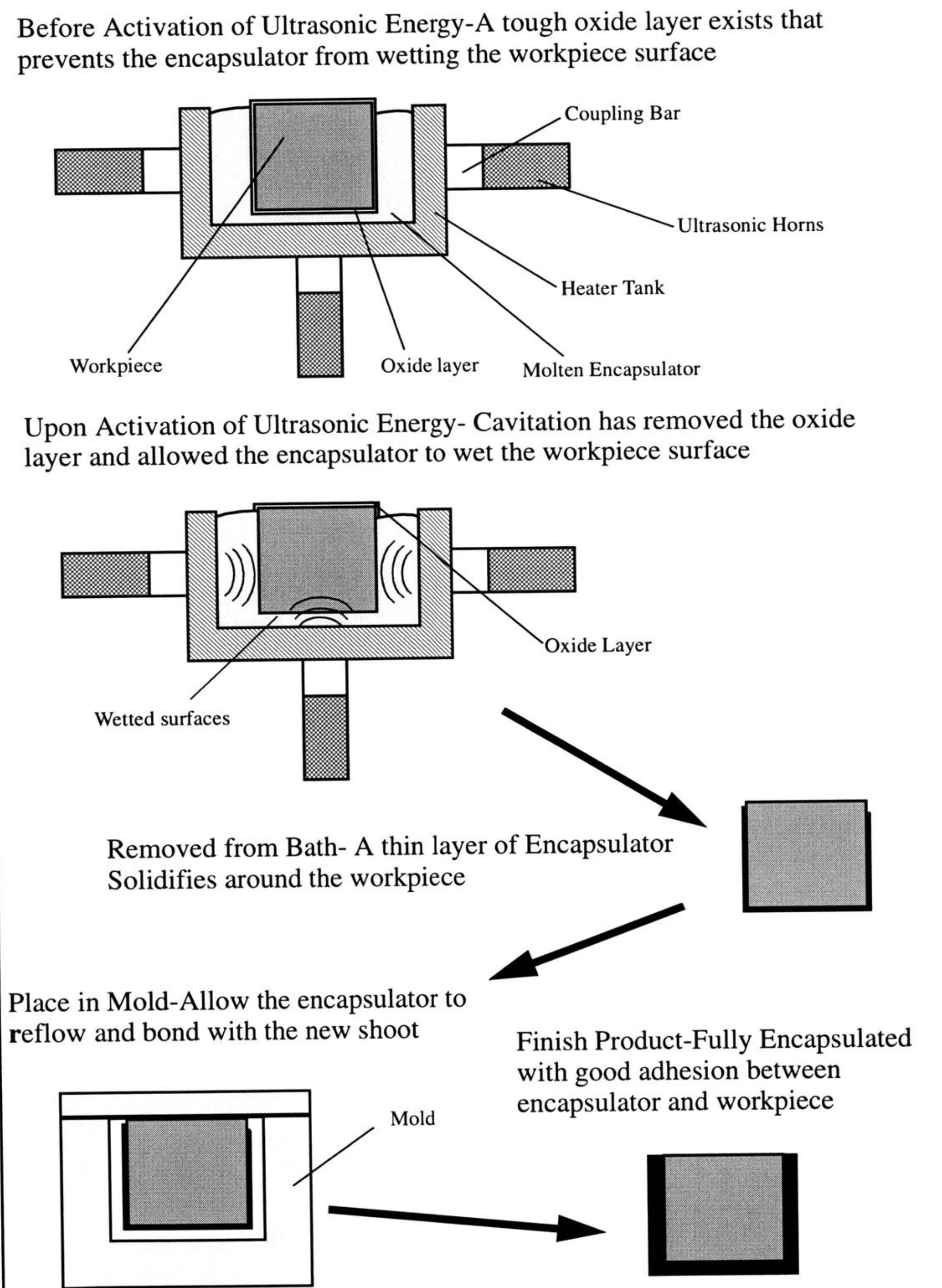


Figure 5.4 Illustration of the modified encapsulation process using ultrasonic soldering to aid/increase encapsulator to workpiece adhesion

or more power will be required to actuate the ultrasonic horns.

Certain parameters must also be investigated and optimized for this particular use. Soldering temperature was reported by many researchers to have effects on erosion and cavitation intensity. Too low of a temperature resulted in low intensity. Too high of a temperatures results in gross amounts of surface erosion and pitting.

However, once the basic parameters are established, research can progress to new levels. Other hard to solder metals such as titanium and graphite will be an important introduction to the encapsulation technique. Titanium has wide spread usage in the aerospace industry and electro-discharge machining, using graphite electrodes, is the primary method through which most industrial plastic injection molds are created.

5.3 Re-Molding and Weldline Experiments

The strength of the encapsulation fixturing as a whole is mostly dependent on the weldline strength of the encapsulation, formed on remolding steps. On successive encapsulations of the stock, it is vital that the old and new encapsulation form a strong bond. Otherwise, there is little chance that the encapsulation assembly will be able to withstand the cutting forces of a milling machine, especially if adhesion is poor. We are performing experiments on the encapsulation procedure to determine the best process conditions that will facilitate good weldline strength. Parameter such as the encapsulator injection temperature and pressure will be varied. We shall also control the mold temperature as well as the workpiece temperature.

We have design a tensile test technique that shall measure weldline strength. A mold has been designed and constructed that will be used to form "dog bone" shaped tensile test specimens. In the first stage, whole specimens will be formed and removed from the mold. Later, each of the formed specimens will be cut in half and each half will be place back into the original mold. By varying the process parameters stated above, each of the half specimens will be reformed into a whole and removed from the mold. These specimens will thus have a weldline where the cut existed. They can be then placed into an tensile test machine such as an Instron Machine and pulled to failure to determine their tensile weldline strength.

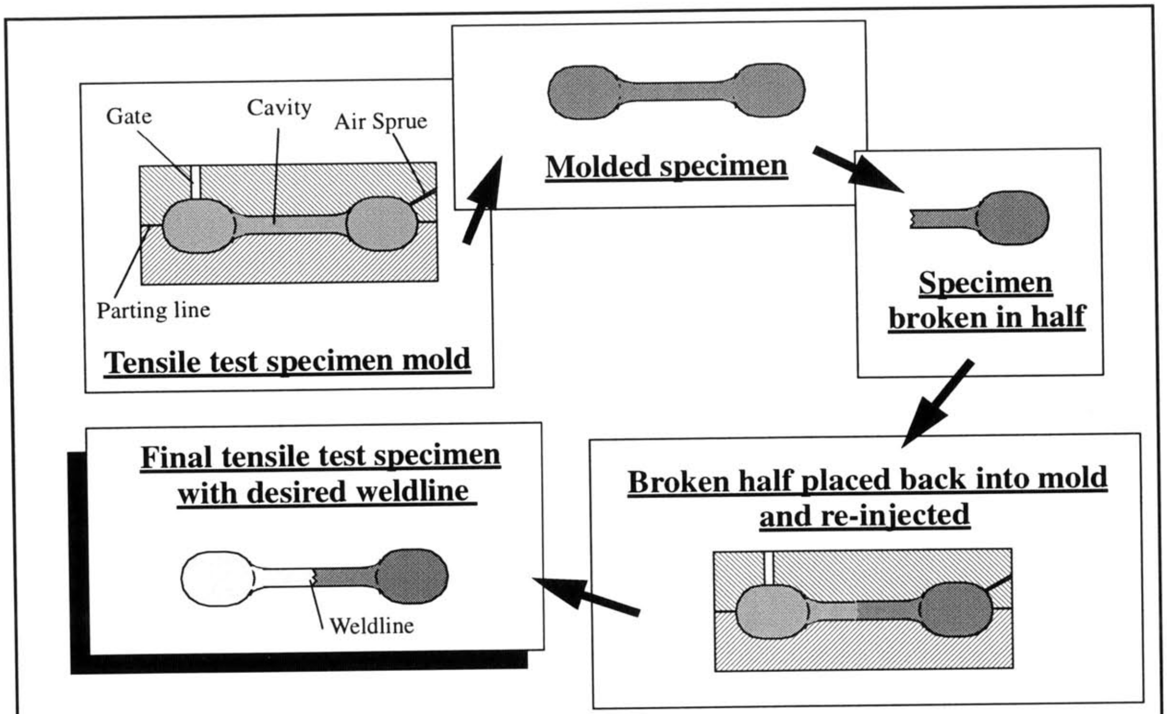


Figure 5.5 Illustration of how weldline test specimens are made

5.4 Melter Device

Another crucial part of the universal automated fixturing system is the removal of the finished part from the encapsulation. It was realized that normal convective heating would not give us the desired rate of heat transfer. To place the specimen in an oven like arrangement and allow heat transfer through natural convection or by some means of moderate forced convection. The maximum average heat transfer coefficient that we can normally expect form force air is about 100W/m^2°C, for subsonic flow. We can calculate the time to melt a 4" block of the Bi/Sn alloy, whose specific heat(C_p) is 167.5 J/°K kg, latent heat of fusion(H_{fg}) is 49,100 J/kg, and density(ρ) is 8580 kg/m^3 using the follow formula:

$$Q = Vol \bullet \rho C_p \Delta T + Vol \bullet \rho H_{fg} \qquad \text{(Eq.5.1)}$$

$$Q'' = 6 \bullet Area \bullet h_{air} \Delta T_{air-block} \qquad \text{(Eq.5.2)}$$

$$Vol = l^3 \qquad \text{(Eq.5.3)}$$

$$Area = l^2 \qquad \text{(Eq.5.4)}$$

If we assume that the heat needed to change the phase of the block will be much greater than that needed to bring the block from room temperature to it's melting point, which is usually the case, then we can simplify our model by saying that the block temperature remains fixed at $T_{melting}$ throughout our entire process. This will allow us to skip the integration over the changing $\Delta T_{air-block}$ as the block warms up. By dividing by , we can calculate the necessary time it will take to melt the block as 12.5 minutes, assuming that the ambient air temperature is about 450°F. Thus, in order to melt a 4" cube within our target time of 5 minutes, the power need would be 7300 Watts. This would be the bare minimum power since we have thus far neglected loses to the environment and the energy needed to bring the temperature of the block up to its melting point.

Several ideas have been generated to design a quicker melting device. The most simple is to dunk the desired encapsulation into a bath of molten alloy. Theoretically, the higher conductive of the alloy will allow considerably higher heat transfer to the block than that of air.

Another possible means of melting the block quickly is by using induction heaters. Induction heaters generate a varying magnetic field around the targeted specimen, which must be electrically conductive, producing oscillatory eddy current inside the part. These eddy currents will then generate heat through resistive heating. Induction heaters develop a skin effect, that is it will only heat up the very top surfaces of our part. To heat up the rest of the part we must rely on conductivity to transfer that heat into the block [Tudbury 60]. We can use this to our advantage. If we can deliver the heat into the top surface quickly enough, so that conduction will not have enough time to transfer the heat inward, we can use most of the heat energy to melt the encapsulation, layer by layer, and leave the embedded stock relatively unheated.

Lastly, it was conceived that a melting device could be designed using hot jets of saturated steam impinging onto the block surface to completely remove the low melt material from the finished part. The key to a high heat transfer coefficient between the steam and encapsulation material is to allow the steam to condense onto the encapsulator surface. However, the saturated steam must condense at temperatures above the melting temperature of the encapsulator in order to melt off the encapsulator. In order to accomplish this, the melting chamber must be atmospherically isolated and the pressure within must be maintained at a value that is equal to the saturation pressure of water at the melting temperature, or slightly above, of the encapsulator. According to steam tables, the pressure needed to maintain saturated steam at 290°F is approximately 65 psi. The use of impinging steam jet method is attractive for a second reason. The encapsulation process often leaves residue on the finished part that must be otherwise picked off manually. However, the strong stream currents will, as it melts the encapsulator, force this residue from the workpiece surface. The jets of steam can thus clean and melt the workpiece at the same time.

5.5 Automatic G-code Parser and Queue scheduler Programming

Any piece of automation is only as useful as the programming that runs it. The universal fixturing system would only be a collection of unusual hardware without an overall controlling program that allows each part to communicate with each other. The goal has always been to create a fully integrated, automated machining process. This certainly would not be possible if the software used to control our fixturing system was not equally integrated and automatable.

The software would have two primary tasks. The first would be to parse G-code created by operators and CAM packages into discrete segments, between which refills would be scheduled. The software should be able to automatically take hundred and thousands of lines of G-coded needed to completely and successfully machine a given part and determine the most optimal places to stop the machining and schedule a refilling. Such can be decided based on simple rules such as those described in section Machining Thin Members and Odd Shapes of chapter 2. It will then be balanced by the length of time it will take to finish the milling process of each G-code segment. Too long of a G-code segment will increase the average leadtime of parts

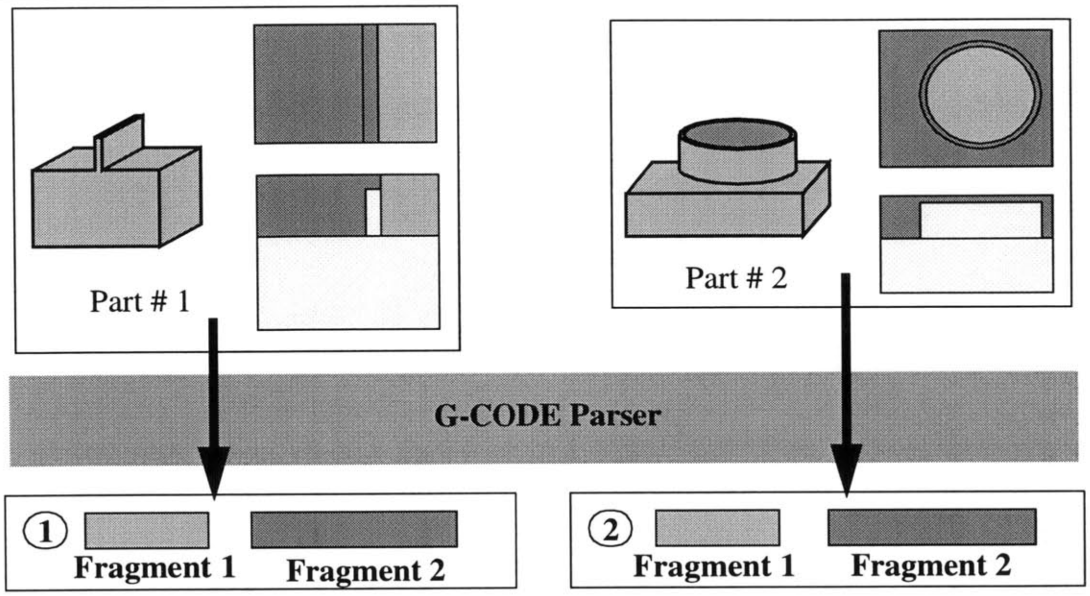


Figure 5.6 Illustration of the G-code parser module: It will take completed lines of G-code built by operator and CAM software and parse it into fragments according certain rules and time length needed to complete the fragment.

going through the process. Too short of a G-code segment increases the number of setups needed to finish a part and thus decreases the throughout of our machining process.

The second task would be to que and track each part as it travels through the system. In our automated environment, 10's if not 100's of parts can be in the que at once, each waiting to be machined, waiting to be delivered to the encapsulation center, waiting to be refilled, and waiting to be transported back to the machining center once refilled. The software must be able to identify each block, determine what has been done to it, what next needs to be machined into that block, and then for all the blocks in the system, order the G-code segments and schedule each block for the correct procedures. It is a non-trivial problem that involves finding a method of tracking each par, of building and storing a

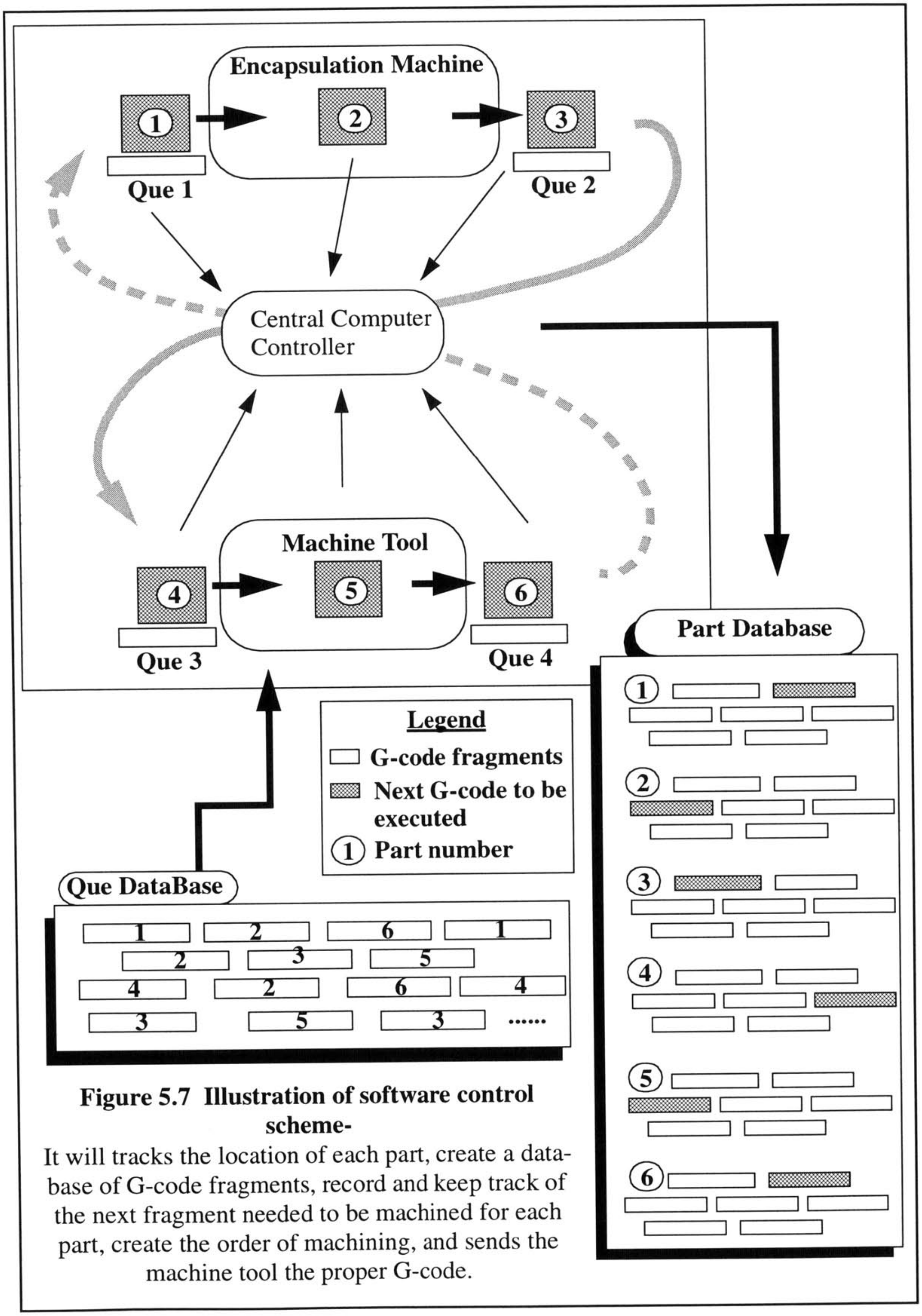


Figure 5.7 Illustration of software control scheme-

It will tracks the location of each part, create a database of G-code fragments, record and keep track of the next fragment needed to be machined for each part, create the order of machining, and sends the machine tool the proper G-code.

database of all the operations needed to complete a part for every part and to mark all the processes that have been completed. A list of rules and guidelines must be developed for the software that will allow it to determine optimal dissection of G-code and optimal scheduling of machining time and refilling time. The goal of course will be to maximize throughput in our system while minimizing the increase in the average leadtime of parts through the system.

We can imagine that the maximum throughput is achieved when there is zero downtime on each of the machining centers, downtime being the total times for setups. The minimum leadtime for a given part can be taken as the total machining time necessary to completely machine the part, ignoring refill, transport and queing times. From these two quantities we can then define process efficiency as:

$$\eta = \frac{Actual}{Maximum} \qquad (Throughput) \qquad \text{(Eq.5.1)}$$

and the fixturing effectiveness as:

$$\varepsilon = \frac{Minimum}{Actual} \qquad (MachineTime) \qquad \text{(Eq.5.2)}$$

By optimizing these two quantities, we can deliver a competitive fixturing system.

5.6 Conclusion

Having developed a viable encapsulation process and the hardware necessary to deliver quality encapsulations into a machine tool, we are one step closer to realizing a fully automated universal fixturing system. However, as this thesis has describe the work that we have accomplished thus far, it also described the many other challenges that lies ahead of us. It is my hope that this research will spark the interest of industry and academia alike and our efforts in this research will be a building block for others in the future. We are one step closer, but still many steps away from our final destination.

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