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CNC Application and Design

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by

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Abstract

Machining is an important manufacturing process that is used in a wide range of applications. From aerospace applications to the manufacturing of energy systems and medical robots, we see a major reliance on machining. In this project we focus on gaining an improved understanding of the mechanics of machining and the different factors that contribute to part quality. We acquired primary machine shop skills that provided us an opportunity to mill and drill a class of components to specified dimensions and tolerances. For each component, we created a detailed engineering working drawing that helped to shape and construct all the operations and procedures that must be undertaken and controlled to attain component machining without any breakdown or failure. Through hands-on machining, we discovered many different factors involved in milling, drilling, and the effects they exhibited on the tolerance and surface finish of a part. The main relevant factors that we examined were tool selection, speeds, feeds, and material selection. The extent to which these factors can influence machining is presented. The MQP project establishes new ways to systematically perform machining in a safe and stable manner without impacting the quality of the surface finish.

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Chapter 1: Background

Introduction

Conventional Computer numerically controlled (CNC) machining is a technology which has been in existence for some decades and is reaching what appears to be an apex, much in tune to the long history of machine tool evolution. This is important as one may realize that while it is an integral step to the industry of tomorrow, it is the culmination which has set the manufacturing industry in an entirely new direction. Understanding and applying this concept as a company is as important as understanding and applying the knowledge as a machinist. Making use of techniques and procedures which maximize the benefit of conventional CNC machining will add value to the machinist, and company, while ensuring that he or she is well-desired in a competitive economy (*Engineers edge.*).

1.1 What Is Machining?

Conventional machining is a general term which refers to the selective removal of material from a part or work piece. The scope and evolution of machining has broadly expanded over the past millennia, especially within the past few hundred years since the advent of the first industrial revolution. More recent advances in machining technology have made it possible to replicate extremely small tolerances on a large scale and exhibit superior finishing characteristics (Erdel, 2003). Improvements such as these can eliminate entire steps from the machining process, thus freeing up valuable productive time. The culmination of related technologies results in conventional CNC machining as it is today: Complex machining centers which are capable of sustaining extended production cycles free from human intervention and offer maximum levels of control and feedback. With computer automation reaching new plateaus, new industrial processes are undergoing development every day. Conventional CNC machining is at an arguable apex with a plethora of highly advanced cutting tools and high-power spindles capable of speeds exceeding 50,000 revolutions per minute.

Figure 1: Example of a mold created using high-speed, 5-axis machining.

http://www.ewt3dcnc.com

Alternatives to conventional CNC machining are presenting themselves as time marches forth. With the unveiling of processes such as Plasma-Arc or Electro-Chemical Erosion, the manufacturing industry finds itself with many seeming viable options in which to create a part. These high initial investments may leave a company uneasy in making a selection as one must be confident that they are making a wise long-term investment which will help ensure survivability. Due to the relative cost and versatility, conventional CNC machining remains as a staple of industry by making it possible to manufacture large quantities of high-quality goods at unprecedented speed. This rapid, high-tech, production enables further advances in virtually all other fields and results in a highly sophisticated world which immerses much of humanity on a daily basis.

1.2 The Origins of Cutting

Cutting as a mechanical process is the removal of material resulting through use of force, typically shear and compressive. Although "cutting" is certainly a cutting process, grinding, milling, and drilling are also cutting processes as they result in material removal through the application of appropriate forces. It is important to recognize this disconnect as it separates "conventional" machining from machining. A good example of a machining process which does not result in cutting is rolling.

Rolling is a machining process in which material is deformed as opposed to removed. It is possible to substitute material removal for deformation and vice versa, though the two tend to not be interchangeable as each has its own specific purpose along with relevant advantages and disadvantages. However, a good machinist understands this and may choose the appropriate process in order to maximize efficiency. The technical aspects of machine cutting will be discussed further in Chapter 2.

The first cutting implements were fashioned from any material which may yield a useable surface or point, typically wood and stone. Tools such as chisels have been found and dated back to 1,500 B.C.E. in Egypt, and saws since the early Stone Age (Michael & Fagan,). The early emergence of these tools is undoubtedly the result of intrinsic simplicity coupled with the abundance of appropriate materials from which to make tools (e.g. flint).

A good example of a modern machine cutter is a punch press. Typically used in sheet metal manufacture, a punch press is capable of rapidly cutting semi-intricate shapes in a single motion. This is achieved through the use of a crafted die which is applied to a work piece with high levels of force. Assuming successful operation, the resulting contact with the cutting and forming surfaces produces a piece which fits the dimensions of the die. This process carries the advantages of high-speed and a low-cost of production. The disadvantages of this process are reductions in quality control and the limitation of the workable material thickness (hence why these operations are best suited for sheet metal).

The Origins of Grinding

Grinding is a process in which an abrasive material is applied with force to induce an eroding effect, commonly used during the finishing of a part. Careful selection and application of this technique allows a machinist to feature a part or eliminate surface flaws. Grinding thus finds a few niches throughout the machining process in which it is of high value. The technical aspects of machine grinding will be discussed further in Chapter 2.

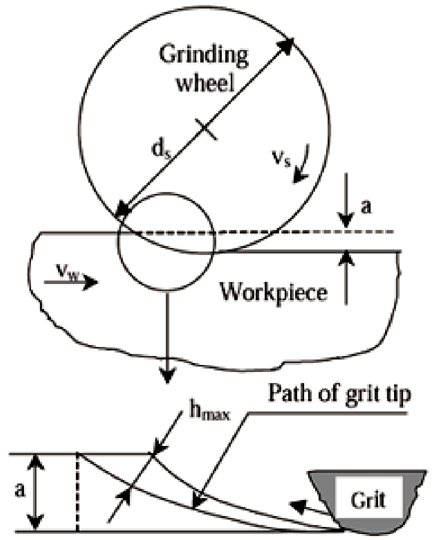


Figure 2: This image shows the forces involved in grinding, from which one can infer the basic mechanisms and principles

(Degarmo, Black, & Kohser, 2003)

In Figure 2, D_s and V_s are the diameter and velocity of the wheel, respectively. V_w is the velocity of the work piece, "a" is the desired thickness of material removed, and h_{max} is the maximum thickness removed at any one time in the grinding process. The grinding that takes place between a metal file and a work piece is the same as that found between particle-laden winds and a canyon. A large number of individual cutting surfaces are applied with consistent force to remove relatively small portions of material at a high frequency. This tends to exhibit features more reminiscent of eroding, though grinding may also be used as a means of cutting through more difficult materials.

1.3 The Origins of Turning

Turning is a process in which the selected material or work-piece is secured at one or both ends and rotated at a high speed. A cutting tool is then introduced so that material is removed in a helical pattern. First appearing around 1300 B.C.E., the ancient Egyptians performed a crude process which replicates the action of a dedicated lathe. One person would use a rope to turn the material (typically wood) while the other would use a cutting tool with their hands. This process is improved upon by the Romans by utilizing a simple bow, but remains mostly reserved for woodworking and pottery until the Industrial Age enables practical metalworking. The technical aspects of turning will be discussed further in Chapter 2.

Figure 3: This is a picture of the Haas Automation TL-1 metal lathe.

http://www.haascnc.com

Somewhat similar to a mill, a lathe turns the work piece as a cutting tool is introduced. A lathe enables one to produce a part with rotational symmetry, or even perform complex helical cutting operations. Examples of these products include baseball bats and worm gears, both of which would be extremely complicated or impossible on a mill. Thus, lathes hold a dedicated position in any machine shop and may even be responsible for the creation of the first true mills.

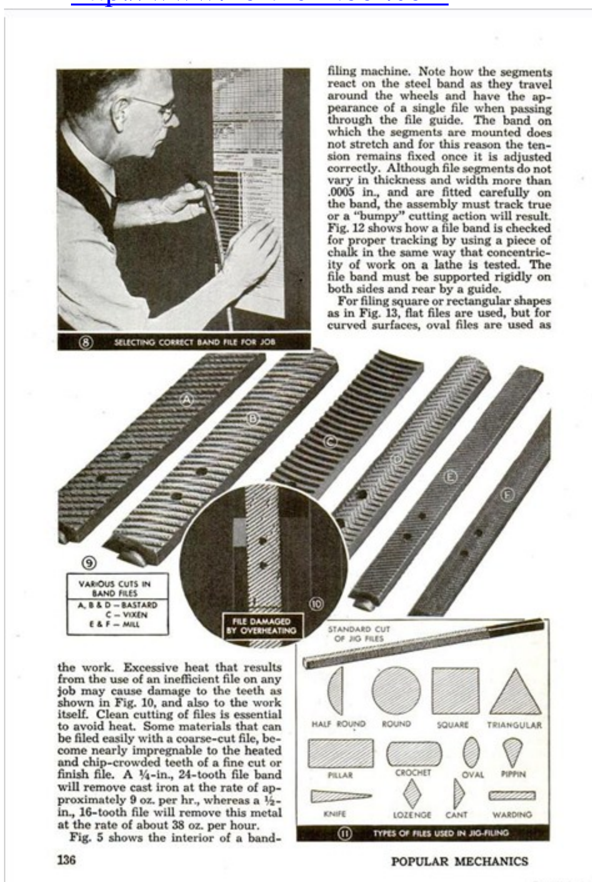
1.4 The Origins of Milling

Mills are machines which are similar in appearance and style to the drill press but differ in function and use. In addition to cutting surfaces on the bottom of a mill bit, the sides are utilized as well. This greatly expands not only the functionality of milling, but also greatly reduces the need for extremely large inventories consisting of cutting tools which may rarely see use. Modern mills employ a variation of cutting tools, such as face, end and ball-mills. Utilizing tools such as these allows for operations such as slot cutting, planning, drilling, contouring, and die-sinking (though more exist). This broad range of use allows a skilled machinist to tackle many of the machining tasks commonly encountered. Mills have not always been this versatile, however, and may have in fact begun with rotary filing.

Rotary filing is a process in which a specialized file is rotated against the surface of a work-piece. Much like a bastardization of grinding and milling, rotary filing only falls short in comparison to a true mill. A rotary filer may be produced as a dedicated machine, though the original use likely came by means of utilizing a round-type file in a typical lathe. Reciprocating files are similar in function, but are historically distinct as reciprocating files emerge later in time and do not influence the development of “true mills” (Scott, 2008).

Figure 4: This is a good example of a small set of rotary files, or burr bits. Note the fluted design indicative of modern tool production.

http://www.northerntool.com



filing machine. Note how the segments react on the steel band as they travel around the wheels and have the appearance of a single file when passing through the file guide. The band on which the segments are mounted does not stretch and for this reason the tension remains fixed once it is adjusted correctly. Although file segments do not vary in thickness and width more than .0005 in., and are fitted carefully on the band, the assembly must track true or a "bumpy" cutting action will result. Fig. 12 shows how a file band is checked for proper tracking by using a piece of chalk in the same way that concentricity of work on a lathe is tested. The file band must be supported rigidly on both sides and rear by a guide.

For filing square or rectangular shapes as in Fig. 13, flat files are used, but for curved surfaces, oval files are used as the work. Excessive heat that results from the use of an inefficient file on any job may cause damage to the teeth as shown in Fig. 10, and also to the work itself. Clean cutting of files is essential to avoid heat. Some materials that can be filed easily with a coarse-cut file, become nearly impregnable to the heated and chip-crowded teeth of a fine cut or finish file. A ¼-in., 24-tooth file band will remove cast iron at the rate of approximately 9 oz. per hr., whereas a ½-in., 16-tooth file will remove this metal at the rate of about 38 oz. per hour.

Fig. 5 shows the interior of a band-

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Figure 5: This is a good example of reciprocating files, retrieved from an article published in a 1943 issue of Popular Mechanics. Note the discussion on proper alignment affecting surface finish and material removal rates. One can also observe more clearly the

http://www.northerntool.com

The actual production of a true mill can be traced to the release of the milling machine in 1825 and is attributed to Eli Whitney. The mill appears to have been developed and created by more than just one person (Woodbury, 1960). Although Whitney is a well-known inventor of the time, his work is more focused towards the American System of Engineering (Http://www.eliwhitney.org.). Credit is instead placed with the contributions of several inventors during over a period of time. These figures include Thomas Blanchard, Simeon North, Roswell Lee, John Hall, and Robert Johnson (Woodbury, 1960).

1.5 The Origins of Drilling

Drilling is a machining process in which holes are either created or enlarged using a bit which is closely related to the end mill. A standard drill bit is nothing more than a shank with a cutting bit which, when turned, creates a cylindrical profile. Many bits are created using a fluted design which greatly aids in the removal of material chips from the work area. Also of great influence to the bit design is the specified range of drilling depth. While shallow holes may be drilled out with confidence, deeper holes (such as those required for the barrels of small and large arms) require more specialized bits capable of actions such as self-centering. The technical aspects of machine drilling will be discussed further in Chapter 2.

The earliest known examples of drilling include the use of bows. Similar to their application in early lathes, bows provide a convenient source of low-technology, hand-held translational power. Though this does allow for more efficient use of power as well as additional control, it is more suited for smaller crafting of non-metallic goods and serves better as a predecessor to more “industrious” technologies.

Figure 6:This image is of two Egyptians using a bow drill for the purpose of carpentry. Excessive friction causes flammable surfaces to burn, and is testament to the tool work piece contact present in drilling.

http://www.world-mysteries.com/alignments/sar_djed.htm

Metal drills were eventually crafted during the Bronze Age between approximately 3,500 B.C.E. to 1,100 B.C.E. It is during this period in time that humans developed the metallurgical technology to produce stronger, more complex designs out of materials which were previously prohibitively difficult to manufacture on a useable scale (Www.britannica.com/EBchecked/topic/81017/Bronze-age.). Drill bits of the time were created by forming a spade at the end of a shank. Referred to as a spoon or spade-drill, these rudimentary tools were capable of drilling to specification, which may not be approached with other tools. Drilling is still limited in capability, but this changed in 1863 with the patenting of Samuel Morse`s twist drill bit.

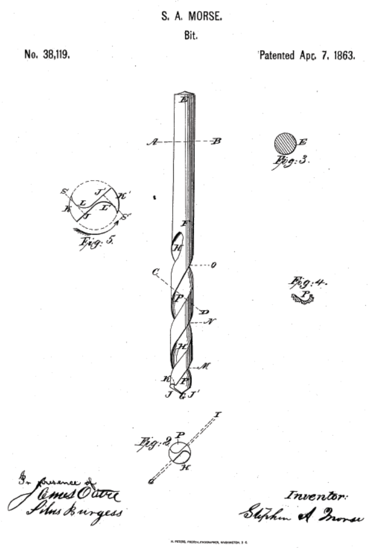

Figure 7: This is a picture taken of Samuel Morse`s patent of a twist drill bit.

(Michael & Fagan,)

Non-fluted drill bits run the risk of tool-work piece interference when certain a depth is reached. This condition is alleviated with the addition of symmetrical flutes which run down past the shank of the drill bit. This allows for chips to travel up and out of the bit in a fashion reminiscent of an Archimedes water screw. The fluting also allows for coolant to be circulated throughout the cutting surfaces further aiding in chip removal and temperature moderation.

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thousandth graduation on the barrel. Once the extension is adjusted, the variation in ten-thousandths can be read directly and without strain from the pointer *b*, which is made from a strip of sheet metal just a "hair" wider than the micrometer frame, so that it can be clamped simultaneously with it.

Detail *C* shows the same appliance made more permanent by the addition of a brass sleeve *c*, which clamps the cardboard segment. This sleeve is made slightly oval so that it will be a good frictional fit on the barrel. Though no micrometer made will measure *absolute lengths* to within less than one ten-thousandth, yet *differences* of half a ten-thousandth can be readily detected with the help of this device.

Old Bill
Talks Shop

WHEN you take over work another man has started, check the entire job to know where you stand; it will save time.

Tapped holes should be cleaned out before sending a part to be heat-treated or some small bits of steel may become welded in place and later cause the screw to be damaged.

A belt that is slowed down by hand should be cemented, not wire-laced.

For highly finished work of the better grade, it is well to equip the parallel clamp with false jaws to prevent marring the surfaces.

Old Bill, foreman of a machine shop.

To assure a true slot on a milling machine, first indicate the cutter, and then use a fine feed.

A hard wheel, if used for grinding hardened steel, may cause cracks.

See that the teeth of a gear cutter or forming cutter are radial before using it.

Study your tool catalogues; they have a wealth of useful information.

A thin-nosed pair of pliers will often remove a broken tap.

Always consider this: If you were the inspector, would you pass every bit of your own work?

Discarded leather belting makes good false jaws for the bench vise as well as handles for small files.

What to Do When Drills Dig In

WHEN a twist drill is used to enlarge a hole that is only a little smaller than its own diameter, it often "digs in" and "hangs up," especially if the material is brass. It may be broken and in some cases may even cause personal injuries if the work is held by hand on the press. By changing the shape of the point slightly, however, the drill can be made to feed smoothly under these conditions.

The accompanying diagrams will help to make this important point clear. The screwlike flutes of the twist drill *A* draw the chips out of the hole but also exert a pulling-in force on the drill. At *B* is the straight-fluted drill used on special work such as brass and thin plates. It has no tendency to feed either in or out. At *C* is the twisted reamer. In use it is rotated in the same direction as the drill, but its flutes slant the opposite way and that makes it push back when at work.

These three tools illustrate the effect of the twist. It is this twist that causes the drill to dig in when used as a reamer. There being no metal toward the center to hold it back, the drill "screws in" too fast.

Just a touch on the emery wheel can change the digging-in drill A^1 into one that pushes back, C^1, or to one that does neither, B^1. Grinding 1/16 in. or less from the end up is sufficient unless a very heavy feed is used.

Another way to prevent gouging that is quite effective and sometimes more convenient is to drive a wooden plug into the hole that is to be drilled out a little larger.

When an attempt is made to drill thin plates, the screwlike flutes cause another difficulty. As the drill goes through, the plate itself is lifted, twisted, and even crumpled up. By grinding the drill as at C^1, a much thinner plate can be drilled on account of the holding-down effect of the forward slanting flute. Because of the springy nature of the material, it is necessary that the flat extend farther up.

If the plates are too thin to be drilled in this way, they can be clamped between two thicker plates, or sometimes two pieces of wood, and a regular drill used.

Where the material is hard, in addition to using the customary slow speed and turpentine, grind the drill as at B^2. The cutting edges will then stand a heavier feed pressure and also dissipate the heat better.

IT IS sometimes difficult to set an odd-shaped piece so that a drilled hole will come out at the right place or, if drilled from each side, so that the holes will meet fairly. This can be nicely done in the lathe. A good center is made where the hole should come out, and this is placed on the dead center. The drill goes in the live spindle. The hole is drilled halfway through, the work reversed, and the other half drilled. The work should be held against the dead center with a lathe tool as at *D*; if not, there is almost certain to be trouble when the holes meet. This precaution should always be taken when the drill is in the live spindle, or bad wrecks may follow.

When a drill in the tailstock is brought up against a piece in the revolving chuck, it does not generally start centrally. The quickest way to center it is to steady it with pressure from the cutting-off tool. This is an old trick, but is often unsuccessful because one point has been overlooked. If the set-up is as at *E*, the drill can wobble in spite of the pressure put on it. The correct arrangement is shown at *F*, where the cutting edge will be held against the "short" side of the hole as it comes around. Then in a few revolutions as the drill is fed in, the wobbling will stop.—John A. Cook.

Diagrams showing how a twist drill can be modified for special purposes, and two hints on drilling in a lathe

Figure 8: Article from Popular Science which discusses how to perform orbital drilling by hand.

(Popular Science Monthly, 1930`)

1.6 Machining and Industrialization

1.6.1 Pre- and Post-Modern Machining: A Basic Comparison

The modern definition of a machine consists of the integration between the machine itself (e.g. a mill), a cutting tool (e.g. an endmill) and a power source (e.g. an electric motor). Note that the given configuration conjures the image of a typical machine center found in today`s industry. One should also pay attention to the difference between a milling machine and a milling machine-center. Machine centers are newer advents in manufacturing and represent a large step in the direction of full automation, though the only major discernment is the inclusion of an Automatic Tool Changer (or ATC). On-board computing systems are also a major part of what makes a machine into a machine center, but would rarely (if ever) be absent from a machine with ATC capability. Union of the systems not only eliminates the need for a human operator to switch out tools during machining operations (assuming sufficient magazine storage), but eliminates most of the time spent performing the actual process as well.

Figure 9: The Haas Automation VS-1, an example of a robust, modern machine-center.

http://www.haascnc.com

The current standards are certainly impressive, although one may dissect such a device into fundamental groups. It may be difficult to envision an example of a machining center, such as the Haas VS-1, parallel to a steam-driven arbor mill, but in fact the only differences are the output rates, versatility, and of course the enormous convenience, accuracy, and precision of computer numerical control. Both examples are still comprised of the machine, tool, and power source.

1.6.2 The First Industrial Revolution

The First Industrial Revolution takes place between the 18^{th} and 19^{th} Century. As the name implies, it is during this time that society begins a mass shift towards industrialization.

Applied technology is coupled with the development of logistic and informational infrastructure. Factories are established, complete with distribution networks, to sell off previously unheard of quantities of finished goods (Http://www.britannica.com/EBchecked/topic/287086/Industrial-revolution.).

One of the most important developments during this time is the Watt steam engine and how it allowed industrialization to take place regardless of geographic location. Freed from hydro-mechanical dependence, factories no longer required placement adjacent to moving water (such as a river). Though wind power is traced as far back as the 1st Century C.E., it is far less reliable than water power and even more unpredictable in terms of impulse. Steam power is thus the first power source which allows for true industrialization.

Explored in ancient Rome (though absent at the time was the realization of its true value), steam power did not make much of an emergence until around the 16th Century. Steam power finally saw its first significant advance with Thomas Newcomen`s 1712 patent. The Newcomen engine is known to be inefficient, but still powerful, though this changed when James Watt greatly increased engine efficiency with a modification made in 1769, and the Industrial Revolution sees its defining achievement.

1.6.3 The Second Industrial Revolution

While the Industrial Revolution contributed to the first true ascension of machine tools, this introduction of mass production conflicted with the high price of material and high waste output intrinsic to machining operations. The process of machining is efficient with regards to production rate, but a majority of the material tends to be removed. The most common material worked with at the time was iron, it was the unveiling of the Bessemer Process in 1855 which provided a steady, stable output of high-quality, low-cost stock. Progress in manufacturing technology continued well into the 1900`s, where war efforts further drove the expanse. It is also during this time that the first working computers are created. As computational technology advanced into the mid-1900`s, entirely new forms of machine automation were explored.

1.7 Numerical Control

Numerical control is the operation of a machine via encoded data inputted on some form of storage device. Machines running NC infrastructures first emerged during the 1950`s and are credited to the vision of John Parsons. Machines of the time were operated via hand-cranks which are manipulated by a machine operator to achieve desired tool positioning. Though a machinist may not have to perform as many operations during linear interpolation, it is during circular interpolation (along with other such complex maneuvers) that the benefit of numerical control is maximized. Numerical control is thus a form of proxy for a machine operator`s movements, and the freedom offered is invaluable to production capacity.

1.7.1 Role of MIT Servomechanisms Laboratory and Parson`s Vision

It is during 1940 at the Massachusetts Institute of Technology that Gordon Brown establishes the Servomechanisms Laboratory. As a product of the electrical engineering department, projects typically focused on control systems specific to military applications and the wartime effort. It is in 1949 that the Servomechanisms Lab was awarded a contract to develop a numerically controlled milling machine for Parsons Company (Popular Mechanics, 1943). Numerical code is entered via "punch tape" (typical encoding medium of the time) and deciphered by the machine controller. Each punch corresponds to a predetermined value and allows the machine to move independently of the human operator. This system is successfully demonstrated in 1952. The Servomechanisms Laboratory continues work writing a machine code language (among other things) in addition to promoting numerical control for industrial use (Popular Mechanics, 1943).


An Automatic Machine Tool

Feedback control has begun to advance in the working of metals. Presenting the first account of a milling machine that converts information on punched tape into the contours of a finished part

by William Pease

SAMPLE PRODUCT of the automatic machine tool described in this article is the cam shown at right. The instructions which direct the cutting of the cam from a square blank are encoded on paper tape.

Figure 10: This article is from a 1952 issue of Scientific American (note the date relative to the advent of numerical control). The picture contained within is an excellent example of punch-tape and numerical control. One can see just how much "code" is required

(Http://blog.modernmechanix.com/2006/04/05/an-automatic-machine-tool/.)

1.7.2 RS-274D

As the advantages of numerical control became apparent, license applications for automated machines greatly increased. Proprietary code that was originally used is still in use, although the Electronic Industries Alliance made a push in the 1960`s for a unified machine code. A finalized index was released in 1979 and designated as RS274D. The implications of this system were enormous as it allowed the industry to maintain a focus on hardware and machining operations while one authority ultimately maintained control over encoding mechanisms.

G-Code is unlike traditional computer code as it does not directly handle any calculations but rather tells the machine what to do and where to go. To better illustrate the point, G-Code may be better thought of as a system of road signs which guide the machine to the end destination (in this case a work-in-progress or a finished piece). This also greatly simplifies the syntax of the actual code, greatly increasing readability. Though initial programming did not benefit from this, the ability to interpret the immediate intentions of a machine on the fly may allow a skilled operator to perform an abort cycle in time to avoid a crash.

Preparatory G-Code appears as an uppercase G followed by up to three numbers valued at 0-9. Also referred to as G-Code, this class is directly responsible for controlling the machine during operation. As the machine reads each line, it is "prepared" for the next cut. The following list is comprised of G-Code used in Haas Automation machines. See Appendix D: CNC Code for more information.

1.8 Integration and Importance of Computer Systems

1.8.1 Computer Numerical Control

Numerical control makes a machine easier and more efficient to operate, but performing the calculations and encoding the data is tedious and prone to human error. The incorporation of computers into existing numerical control systems was a convenient solution to these drawbacks, though the merge occurred gradually throughout the late 1900`s. It is during these years that the rapid miniaturization of computational technology results in small, powerful and affordable personal computers.

Proliferation of cheap, reliable computers affects many aspects of the manufacturing industry. As previously described, these computers and eliminated the need for an operator to directly control the machine. It also allows for the development of software which is capable of performing extremely complex calculations faster than humanly possible to do by hand. As the integration evolves, control feedback mechanisms are designed which account for the many variances present during machining operation and prevent full control over tolerances and finish.

1.8.2 Open- and Closed-Loop Machining

Open-loop and closed-loop machining represents the differences between a machine with and without feedback and control mechanisms. An open-loop machine is one which can send signals from the controller to the machine tool, but receives no information in return. This typically represents a basic system which requires human control and moderation. Closed-loop machining processes are those which possess the ability to send signals back from the machine tool to the controller. These signals may contain important information about the current cutting conditions and are very useful in making automatic adjustments during operation. These adjustments help minimize detrimental conditions such as tool deflection or work piece slip. The cost of closed-loop machinery is considerably more expensive than the open-loop counterparts, but offers unparalleled process control.

Figure 11: This image highlights the importance society may place on manufacturing engineers and machinists.

(Popular Mechanics, 1943)

Chapter 2: Overview of the CNC Machining Process

Introduction

The importance of manufacturing and having skilled manufacturers in the United States industry has been apparent since the industrial revolution in the 1800's. The economic change that took place when production went from skilled craftsman to machines and factories has helped make the U.S. the superpower nation it is today. Since the modern industrial revolution took place in 1973 all areas of industry from technologies, politics, and the economy have all been influenced and changed dramatically (Scott, 2008; U.S. Department of Labor, Bureau of Labor Statistics, 2008). The skill of the manufacturing industry is to create a quality part that meets the consumer's specifications for the least amount of money. The progression and advances in manufacturing continue to decrease the cost of production and further decrease the overall cost of goods which, in turn, affects the national economy. Today the U.S. faces the difficult issue of overseas outsourcing manufacturing jobs to countries like China, Thailand, and Japan in order to save on production costs. Although this outsourcing may be useful in the short term and temporarily boost bottom line profit, the recent disaster in Japan show us how dangerous outside reliance can be (Scott, 2008). United States companies are constantly looking for skilled manufacturing engineers and machine specialists to increase their productivity and lower machining costs.

2.1 Importance

Machining is a vital part of the over 14 million manufacturing jobs in the United States alone. The manufacturing sector in the United States encompasses mechanical, chemical, or physical transformations of material into new products (Scott, 2008). Manufacturing is a continuously growing industry accounting for about ten percent of the total employment rate since 2007. Manufacturing skills learned in this project will help us positively contribute to the United States' economic production accounting for about 1.6 trillion dollars in GDP in 2006 alone, and has been attributed to a gross output of 4.5 trillion dollars in the year 2005 (Scott, 2006). Manufacturing also exports about 64 percent of all U.S. goods each year (Houseman, 2007). As shown in Table 1 machinists with the skills we have acquired accounted for 305,610 jobs in 2009 comparatively shown with other jobs in the manufacturing industry.

Table 1: Manufacturing Employment Breakdown for the year of 2009

Data series	Employment, 2009
Helpers--production workers	286,600
Inspectors, testers, sorters, samplers, and weighers	299,450
Machinists	305,610
Purchasing agents, except wholesale, retail, and farm products	98,600
Team assemblers	756,630

(Scott, 2006)

Table 2 shows a comparison of earnings based upon occupation. You can see that with a mastery of machine skills one can expect an average annual income of around 39,000 dollars, which is the second highest of all manufacturing jobs.

Table 2: Earnings by Occupation

Data series	Wages, 2009			
	Hourly		Annual	
	Median	Mean	Median	Mean
Helpers--production workers	$11.21	$11.92	$23,310	$24,790
Inspectors, testers, sorters, samplers, and weighers	$15.85	$16.90	$32,960	$35,150
Machinists	$18.17	$18.78	$37,800	$39,060
Purchasing agents, except wholesale, retail, and farm products	$25.66	$27.04	$53,370	$56,240
Team assemblers	$13.59	$14.52	$28,260	$30,190

(U.S. Department of Labor, Bureau of Labor Statistics, 2008)

Individual state economies are also greatly affected by the manufacturing industry. Table 2 provides a detailed look at the employment status in 2007 and Figure 12 shows the breakdown of GDP for each state based on the industry.

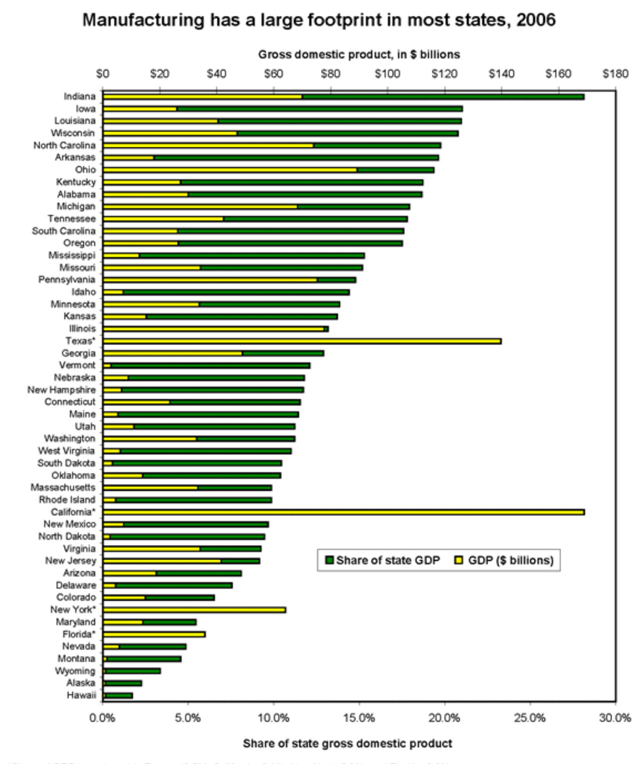


Figure 12: Manufacturing as a Share of State GDP

(U.S. Department of Labor, Bureau of Labor Statistics, 2008)

With the right experience and skill in manufacturing and machining, one has the opportunity to make more money, on average, than jobs in other fields of the economy even without a college degree, as seen in Figure 12. Having machine experience and manufacturing understanding can be detrimental in getting and sustaining an income without a degree, and can greatly increase your starting income with a degree. In addition to the economic contributions of the manufacturing industry, it is also a vital contributor in national matters. Decreasing the United States' dependency on imported energy like oil, and the reduction of greenhouse gas are both directly related to the new materials developed by a vibrant manufacturing industry (Scott, 2008).

2.2 Machining Operations

2.2.1 Milling

Milling is the process of cutting and shaping materials into a desired part. Milling operations are performed on milling machines, gear-cutting machines, and machining centers. Milling machines are complex devices that perform several operations. The actual shaping of the part is done with a cutting tool attached to a spindle, delivering rotational forces. Milling machines have either horizontally or vertically aligned spindles. The machines are either manually operated or Computer Numerically Controlled. In complex operations it is far more effective to use a CNC machine. Milling operations are usually classified as face milling, end milling, and slotting. Important concepts in milling are conventional milling (or up milling) and down milling.

In conventional milling the cutting force runs opposite the feed direction. Constant pressure can be maintained, so backlash has no major effect on the cutting process. One of the negatives of conventional milling is that the cutter sometimes rubs against the work piece. This can considerably reduce both tool life and cutting accuracy. Many modern milling machines have anti-backlashing systems in order to counteract these problems. Conventional milling has a significant advantage when machining materials with high ductility and work hardening properties.

2.2.2 Drilling

While milling is performed in all directions and can create unique parts, drilling is performed only in the axial direction. Drilling can be described as a process in which a cutting tool of fixed diameter is fed into a work piece. It is a very simple operation and the resulting holes share a diameter with the size of the cutting tool. In reality the dimensions of the hole may differ slightly due to the various factors such as vibrations or inaccurate tool alignment. Drilling operations can be performed on a lathe, milling machine, or a drilling machine. It is important to understand that not all drilling operations can be performed on one machine and all three machines perform a type of drilling better than the other. As a result, it is necessary to select the right machine for the specific application.

2.2.3 Turning

Turning is a process that can be done on a machine called a lathe. It allows a machinist to create parts with features that are axially symmetrical. A lathe spins the work piece while the cutting tool removes stock in the radial or axial direction. Turning is used to create concentric features on the outside, inside, or face of a part. Lathes are useful to machinists in many ways; They are often used to create circumferential grooves, screw threads, as well as stepped, tapered, and rounded shafts. Another technique that is used with lathes is boring; this is the removal of material from the inside of a work piece.

2.3 Tooling

Tooling is all precision work-alignment and holding components as well as all cutting tools and tool holders (Oberg, Jones, Horton, & Ryffell, 2000). CNC tooling is design specifically for use with CNC machines and is made with incredible precision so that the operations performed are also precise. In general, CNC tooling can withstand higher temperatures and cutting pressures than regular machine tooling. They are also are more wear-resistant. They are normally made of high-speed steel, carbides, ceramics, CBN’s, and diamonds.

2.3.1 Work Piece Alignment

The first area of tooling to discuss is all the components designed to hold the work piece in the appropriate place during machining, such as types of fixtures, clamps, plates, and blocks. These devices are used for location detection, clamping, and support. If the work piece is not in the right position or if it is not probed properly there is a possibility of the cutting tool hitting the fixtures which could damage it. If it is not clamped correctly the cutting forces may cause it to move, which may create undesired dimensions. Also, if it does not have enough support deflection cannot be minimized. Total equilibrium must be maintained during the entire machining process.

The main fixtures used in CNC machining, especially in mini mills are CNC vises. CNC vises are perhaps the most important features used to constrain a work piece and are normally a permanent component of the machine to hold the work piece in a completely immobile state during machining. Constraining the work piece is essential to produce the desired results as far as specified shape, dimensions, and tolerances.

Figure 13: Vise Fixture for a CNC Machine

(Oberg et al., 2000)

Different types of fixtures can be used to orient the part in different directions. Blocks are also used in conjunction with vises. Their purpose is to prop the work piece up to the height needed so it can then be tightened in the vise, fixing it in the exact spot desired. Clamps can also be used to constrain oddly shaped work pieces or just provide extra stability. Depending on the position of the clamps the CAM program may need to take them into consideration.

2.3.2 Tool Holders and Tool Selection

Tool holders are another essential part of CNC machining. They are not work-alignment components instead their purpose is cutting tool alignment. They are what links the machine to the cutting tool and translates the rotational forces from one to the other. It is vital to the machining operation that the right tool holder is selected. If the cutting tool is held to loosely, vibrations and other forces will compromise the effectiveness of the machining operation. On the other hand if the fit between the cutting tool and the tool holder is too tight there is a possibility that the tool holder may break; this obviously detracts from the effectiveness of the operation and future ones. Though there are several variations of tool holders designed for different purposes, they are all designed to fit securely in a CNC machine. The standard tool holder consists of three main components, the cutting tool, the insert to secure the tool, and the tool holder itself known as a chuck. Chucks fit directly into the CNC machines and are lubricated to prevent friction. Some chucks have permanent cutting tools built in, but most use inserts so that they can be changed, allowing for many different cutting tools to be used. The appropriate insert is housed inside the chuck and held in place by a large nut that also secures the cutting tool.

The most common inserts used are collets and adjustable tool holders. Collets are inserts that hold the cutting tool in place. When selecting the appropriate collet it is essential to pick a collet that is loose around the cutting tool. The collet is then tightened around the cutting tool by turning the nut on the chuck. As mentioned before, if the fit between the collet and the cutting tool is too tight, the chuck it may break it.

Adjustable cutting tool holders are very common and normally found on any hand drill. They are very simple mechanisms that can be tightened and loosened to fit a wide array of cutting tools. They are efficient due to the fact that they are able to use a large amount of collets with one device. However, they are not good for all CNC machining operations because they can become loose easier than tool holders that use collets, they are also not balanced which can cause instability during a machining operation.

2.3.3 Cutting tools

There is an incredible amount of different types of cutting tools used in CNC machining. As a result of this fact, this section focuses only on the tools required to machine the parts we were tasked with producing. When discussing cutting tools it is important to know that there are four critical angles of each cutting tool: end cutting edge angle, axial relief angle, radial relief angle, and radial rake angle. The end cutting edge angle it is the angle formed by the end flank of the tool and a line parallel to the work piece centerline. Increasing the end cutting edge angle tilts the far end of the cutting edge away from the work piece. The axial relief angle is the angle made by a line tangent to the relieved surface at the end cutting edge and a plane normal to the axis. The radial relief angle is the angle formed between a relieved surface and a given plan tangent to a cutting edge or to a point on a cutting edge.(Oberg et al., 2000) Lastly the radial rake angle is the angle formed by the radius and the tooth face. The radial rake angle describes how close to the cutter radius the face of the insert sits. These four critical angles are shown in the Figure 14 below. We mainly used end mills, face mills, twist drills, and tap drills to machine our parts.

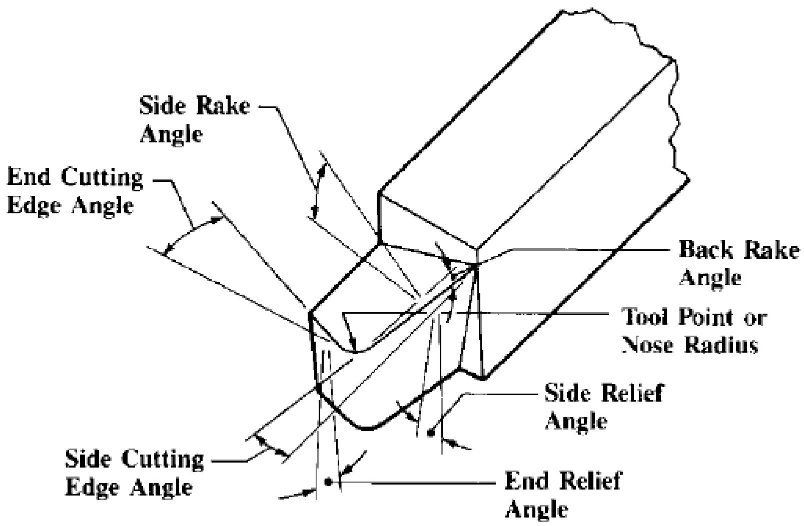


Figure 14: Turning Tool used in a Lathe Machine Tool

(Oberg et al., 2000)

2.3.4 End Mills

End mills are used for milling applications. Though they look similar to twist drills, their geometry is much different and they are used for different operations (Oberg et al., 2000). End mills are used to mill in all directions, but some cannot cut in the axial direction due to their short length. End mills are used for pocketing, profile milling, face milling (not to create a smooth finish), and other small operations such as tapping.

Figure 15: Assortment of End Mill Cutting Tools

metalworkingtool.net

2.3.5 Face Mills

Face mills usually have three cutting edges and are used to take a small amount of material off of a face of a work piece. The blades are very sharp and create a good finish on the surface of the work piece, unlike using an end mill. The most common type of face mill for CNC machining is the 3 inch version. They are normally used for facing aluminum and non-ferrous materials. These metals are considered soft and are easier to machine a smooth surface finish.

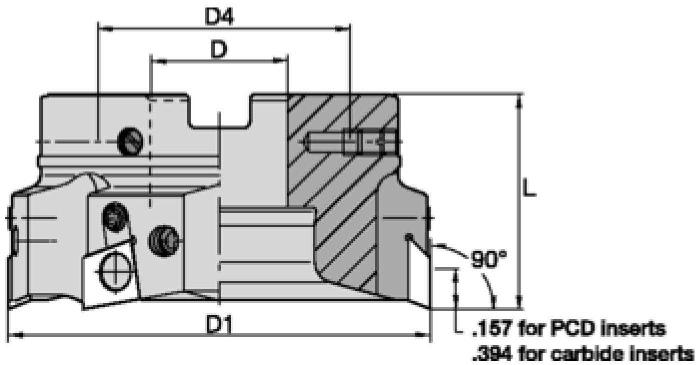


Figure 16: Technical Drawing of a Face Mill

(Oberg et al., 2000)

Twist Drills

There are three general categories of CNC twist drills that are used. They are low-helix twist drills, high-helix twist drills, and coolant feeding drills. Low-helix twist drills are particularly useful for drilling brass, bronze, and hard plastics because the slow helix reduces the rake angle at the cutting lips. They also have polished flutes to prevent clogging by ejecting chips. High-helix twist drills have a fast helix which increases the rake angle at the cutting lips. This type of drill is designed for drilling aluminum, copper, and other soft metals coolant feeding drills are heavy duty twist drills; they are used for cutting the hardest of materials. They are also used to drill deep holes in softer materials. One of the major features of coolant feeding drills is in fact the coolant. It is fed through a hose in the machine onto the drill bit through a directed nozzle. The purpose of the coolant is to prevent the bit from overheating from the friction forces experienced during drilling. If the drill bit is subject to high heats it runs the risk of failing as a result. Coolant is used in many types of machining operations ranging from drilling to roughing (Oberg et al., 2000).

For our drilling operations we only used twist drills with 118° standard point tips. We used number and letter drills ranging from 1 to 60 and A to Z respectively. The reason we only used these drills besides the fact that they were the only types we needed was because they were the type available to us. Nearly every time we performed a drilling operation we used coolant. We did not want to run the risk of damaging bits that did not belong to us for the sake of observing the effects of using no coolant.

Figure 17: Twist Drills

1st-product.com/catalogs

2.4 Analysis

2.4.1 Tolerance

Tolerance is the amount of variation permitted on dimensions or surfaces of machine parts. Tolerances are determined by finding the maximum and minimum clearances required on operating surfaces. The tolerance is the difference between the maximum and minimum limits. For example, if the maximum limit is 5.01 inches and the minimum is 4.99 inches then the tolerance is .02 inches or +/- .01 inches. If you are trying to mass produce a part or make several of the same parts, it is not realistic that every single one is going to be identical. There will always be slight variations so tolerances define the allowable variation in the dimensions that still secure sufficient accuracy. Another important term that relates to tolerance is allowance. Allowance is a difference in dimensions prescribed in order to secure various classes of fits between parts (Oberg et al., 2000).

There are two types of tolerance, unilateral and bilateral. Unilateral tolerance is in one direction only while bilateral is in divided in two directions. For example a unilateral tolerance would be 5.00 +0.01 or 5.00 -0.01 and a bilateral tolerance would be 5.00 +/- 0.01. Tolerances are applied in order to show the permissible amount of dimensional variation in the direction that is less dangerous. If variation in either direction is equally dangerous then bilateral should be used (Oberg et al., 2000). When we our group first started experimenting with different types of fits we used unilateral tolerances because we determined it would be better to make the hole to big than to small so we could at least have some sort of fit instead of none at all.

2.5 Fits

In machining there are many types of fits. Fits are the general term used to signify the range of tightness that may result from the application of a specific combination of allowances and tolerances in the design of mating parts. There are clearance fits, interference fits, and transition fits. These fits between cylindrical parts, such as a hole and a shaft govern the proper assembly and performance of many mechanisms (Oberg et al., 2000). A clearance fit is one having limits of zero so specified that a clearance always results when mating parts are assembled. This type of fit is loose and allows the shaft to have some freedom of motion between it and the hole. Interference fits have a certain amount of tightness and are usually used when the part is meant to remain permanently assembled or taken apart from time to time (Oberg et al., 2000). Usually a press has to be used to insert the shaft into the hole. The last type of fit is the transitional fit. It is one having limits of size so specified, that either a clearance or an interface may result when mating parts are assembled. The reason for classifying the different types of fits is so the designer can specify exactly what he or she wants so machinists can produce the part to the desired specifications. Because of the need to establish limits, tolerances are needed for the shafts and the holes to ensure the desired fit is obtained (Oberg et al., 2000).

2.5.1 Forced Fits

The allowances for forced fits are normally in the range of 0.001 inch to 0.0025 inch and are usually in the cylindrical shape. As the diameter of the cylinder or hole increases, the allowance per inch decreases (Oberg et al., 2000). To determine the pressure required for assembling the part the following equation can be used.

P = (A X a X F)/2

P= Ultimate pressure required

A= Area of surface in contact

a= Total allowance

F= Pressure factor

Table 3: Pressure Factors for Machining

Diameter, Inches	Pressure Factor	Diameter, Inches	Pressure Factor	Diameter, Inches	Pressure Factor	Diameter, Inches	Pressure Factor	Diameter, Inches	Pressure Factor
1	500	3½	132	6	75	9	48.7	14	30.5
1¼	395	3¾	123	6¼	72	9½	46.0	14½	29.4
1½	325	4	115	6½	69	10	43.5	15	28.3
1¾	276	4¼	108	6¾	66	10½	41.3	15½	27.4
2	240	4½	101	7	64	11	39.3	16	26.5
2¼	212	4¾	96	7¼	61	11½	37.5	16½	25.6
2½	189	5	91	7½	59	12	35.9	17	24.8
2¾	171	5¼	86	7¾	57	12½	34.4	17½	24.1
3	156	5½	82	8	55	13	33.0	18	23.4
3¼	143	5¾	78	8½	52	13½	31.7	…	…

Table 3 is the pressure factor for various diameters, based on the assumption that the diameter of the hub is twice the diameter of the bore (Oberg et al., 2000). There are also two other types of fits in this category call expansion fits and shrinkage fits. These two types of fits are complicated and require a temperature change and material elasticity respectively. These fits were unnecessary for us to experiment with.

2.5.2 Standard Fits

The following types of fits all have different classes that make for more specific fits. This list was taken from the (Oberg et al., 2000).

2.5.3 Running and Sliding Fits (RC):

- *-Rc1: close sliding fits are intended for accurate location of parts which must assemble without perceptive play.*
- *-Rc2: sliding fits are intended for accurate location, but with greater maximum clearance than class Rc1. Parts made to this fit move and turn easily but are not intended to run freely, and the larger sizes may seize with small temperature changes.*

- *-Rc3: precision running fits are about the closest fits which can be expected to run freely, and are intended for precision work at slow speeds and light journal pressures, but are not suitable where appreciable temperature differences are likely to be encountered.*
- *-Rc5 & -Rc6: medium running fits are intended for higher running speeds, or heavy journal pressures, or both.*
- *-Rc7: free running fits are intended for use where accuracy is not essential, or where large temperature variations are likely to be encountered, or under both these conditions.*
- *-Rc8 & -Rc9: loose running fits are intended for use where wide commercial tolerances may be necessary, together with an allowance, on the external member.*

2.5.4 Locational Fits (LC, LT, LN):

- *Lc: locational clearance fits are for parts which are normally stationary, but which can be freely assembled or disassembled. They range from snug fits for parts requiring accuracy of location, through the medium clearance fits for parts such as spigots, to the looser fastener fits where freedom of assembly is of prime importance.*
- *Lt: locational transition fits are compromise between clearance and interference fits, for application where accuracy of location is important, but either a small amount of clearance or interference is permissible.*
- *Ln: locational interference fits are used where accuracy of location is of prime importance, and for parts requiring rigidity and alignment with no special requirements for bore pressure.*

2.5.5 Force Fits (FN):

- *-Fn1: light drive fits, require light assembly pressures, and produce more or less permanent assemblies.*
- *-Fn2: medium drive fits, suitable for ordinary steel parts, or for shrink fits on light sections.*
- *-Fn3: heavy drive fits, suitable for heavier steel parts or for shrink fits in medium sections.*
- *-Fn4 & -Fn5: force fits are suitable for parts which can be highly stressed or for shrink fits where the heavy pressing forces required are impractical.*

2.6 Surface Finish

2.6.1 Overview

Surface finish has been an increasingly important characteristic of machined parts since the 1940's. During that time, E.J. Abbot developed a surface finish testing machine which led to some major changes in manufacturing specifications and dimensional tolerances since

(Tabenkin, 2004). The recent development of high speed machines has benefited the machining industry with such things as increased speeds of moving parts, and higher loading. These things as well as gears, shafts, and bearings have resulted in better accuracy dimensionally and geometrically but occasionally leave products with surfaces that are unacceptable geometrically and quality of texture. As a result the industry is beginning to focus more on finishing processes like honing, lapping, and super finishing which are designed to produce particular surface finishes and to correct manufacturing imperfections (Degarmo et al., 2003). The geometry of the surface is measured for two primary reasons. One is to try to predict the performance of the machines used, and the other is to attempt to control the manufacturing processes used. Surface finish has three components, form waviness and roughness. Form or straightness error is the summation of errors in the way the machine produces the part. Waviness is the result of vibration error in both the machine tool and external sources. Roughness is the error caused by the feed-rate tool geometry, variations in material and tool conditions (Davim, 2001).

In order to control the surface finish steps must be taken as early as the initial design. The original design must account for the surface finish that provides the maximum performance and life of the product but at the lowest cost. Primarily there are two reasons to control surface finish. One is to reduce friction, and the other is to control wear (Church, 1988). Friction is an important consideration for finishes because the surface irregularities can cause a film buildup of lubrication between two moving parts. These irregularities must be small enough for the film will not penetrate under both standard and severe operating conditions. Friction reduction is vital in such parts as bearings, piston pins, and gears. Controlling wear is important for the life of the product. Simple wear and tear especially in parts that undergo dry friction, such as machining tool bits without lubrication or brake drums (Tabenkin, 2004).

Surface finishes also contribute to the fatigue strength of stressed members; by eliminating the steepness of the irregularities on the surface, which are at the greatest risk of cracking, one can increase the strength and life of the member. For some parts, controlling surface finish is directly related to controlling noise and is necessary to provide quiet operations. In some cases a rougher surface might be ideal in order to help lubricate members. Most new moving parts also have a wear in period which must be accounted for in the surface roughness. The new parts do not completely lubricate due to imperfect geometry, thermal deformations, and running clearances, and therefore may require some surface material removal in order to fit correctly. The surface finish must be a mixture of roughness for proper break in and smoothness for the actual service life (Tabenkin, 2004).

Measuring Surface Finish

The surface finishing is measured in two general ways skidded and skidless. Skidded measures the roughness of the material only, and uses the work piece as the reference surface. Skidless measures the material for waviness, form, and roughness by using a probe that rests on the work piece and an internal precision reference surface (Degarmo et al., 2003). The process of skidless measuring is shown in Figure 18.

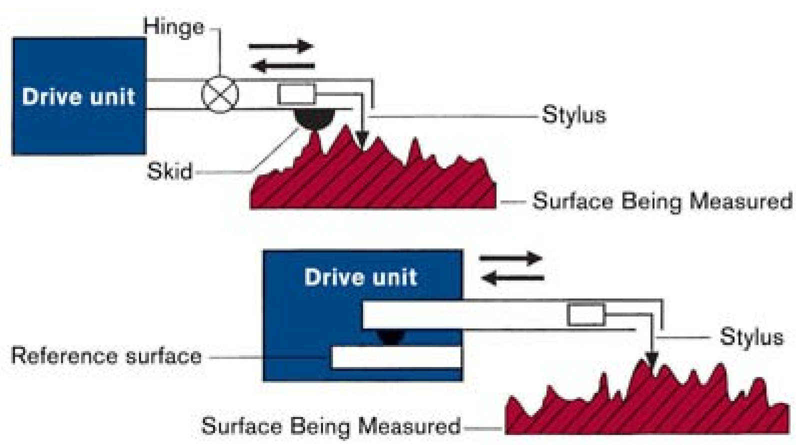


Figure 18: Tools Used to Measure Surface Finish

In skidded gages, the sensitive, diamond-tipped stylus is contained within a probe, which has a skid that rests on the work piece. Skidded gages (upper) measure roughness only. Skidless gages (lower) use an internal precision surface as a reference. This enables skidless gages to be used for measurements of waviness and form, in addition to roughness (Mahr Federal Inc,).

2.6.2 Recognizing Surface Finish

Figure 19 shows the characteristics of surface texture on a standard mechanical drawing of a production part. The symbol is always placed in the standard upright position, never at an angle or upside down. The symbol is generally omitted on views of parts when the finish quality of a surface is not important. In general industry the ideal finish is the roughest one that will still get the job done.

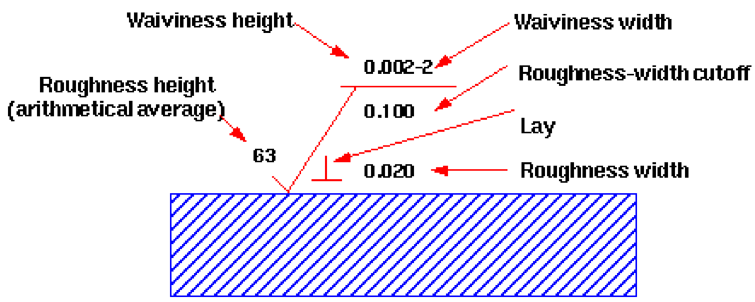


Figure 19: Surface Finish Call Out

In the United States, surface finish is usually specified using the ASME Y14.36M standard. The other common standard is International Organization of Standardization (ISO) 1302.

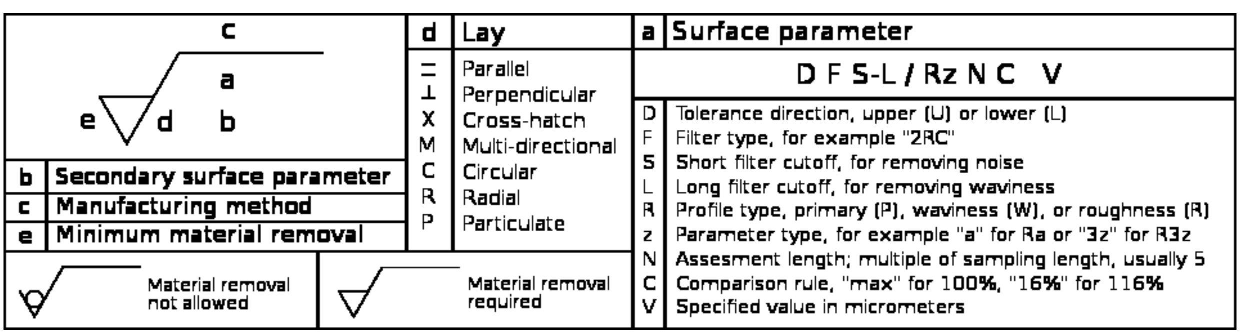


Figure 20: Standard Surface Finish Symbols and Locations

Periodic Profiles	Non-Periodic Profiles		Cut-off	Sampling Length/ Evaluation Length
Spacing Distance RSm (mm)	Rz (µm)	Ra (µm)	λc (mm)	λc (mm)/L
>0.013-0.04	To 0.1	To 0.02	0.08	0.08/0.4
>0.04-0.13	>0.1-0.5	>0.02-0.1	0.25	0.25/1.25
>0.13-0.4	>0.5-10	>0.1-2	0.8	0.8/4
>0.4-1.3	>10-50	>2-10	2.5	2.5/12.5
>1.3-4.0	>50	>10	8	8/40

Figure 21: Recommended Cutoffs for Different Surface Finishes

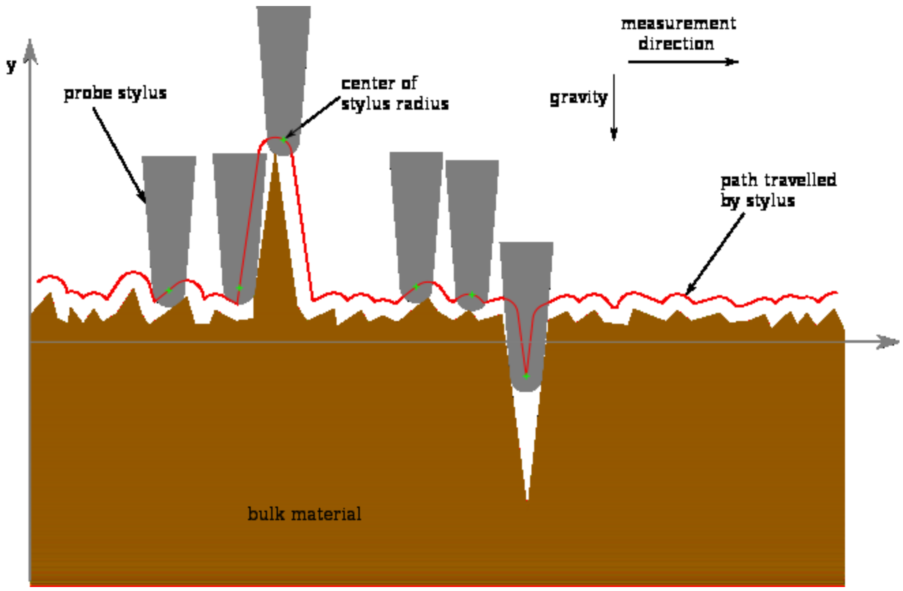


Figure 22: Mechanical Filtering of Surface Finish Trace

2.6.3 Factors Effecting Surface Finish

There are many factors that contribute to the surface finish in manufacturing. In forming processes, like molding or metal forming, the surface finish of the die determines the surface finish of the work piece. In machining the interaction of the cutting edges of the tool and the material being cut contribute to the final surface finish. One of the main contributing factors is the occurrence of a built-up edge. The larger the built up edge, the rougher surface, so eliminating or reducing the built-up edge provides a nicer final surface finish. The height, shape, arrangement and direction of surface irregularities on the work piece depend upon a number of factors such as: the machining variables which include (cutting speed, feed, and depth of cut), the tool geometry (nose radius, rake angle, side cutting edge angle, and the cutting edge). For the most part the cost of manufacturing raises as the surface finish improves. Manufacturing processes result in different tolerances and different roughness (Hirst, 1974). Precise processes with high tolerances create low surface roughness. Figure 22 shows the general tool used by engineers for a variety of surface roughness created by the different manufacturing processes (Degarmo et al., 2003).

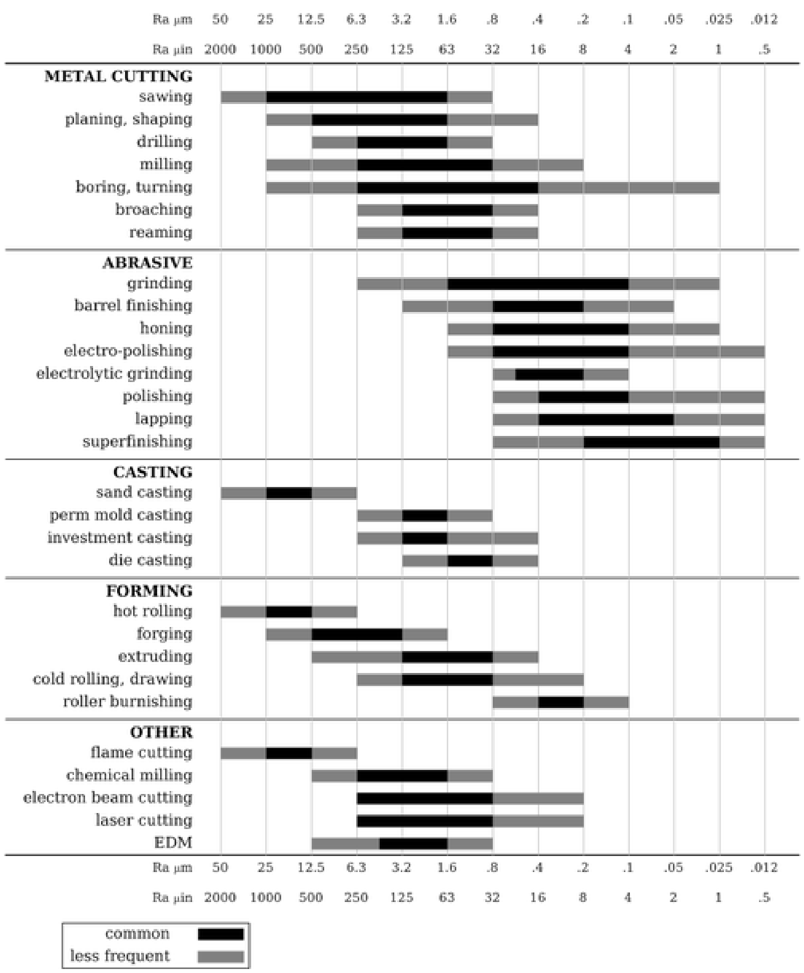


Figure 23: General Tool Used by Engineers for a Variety of Surface Roughness Characteristics

2.6.4 Terminology and Standards of Surface Finish:

The following figures breaks down surface finish terminology and how that terminology applies to the work piece.

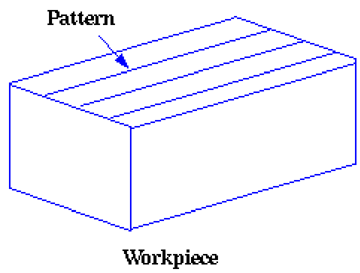


Figure 24: Common Visual Outcome of a Facing Operation

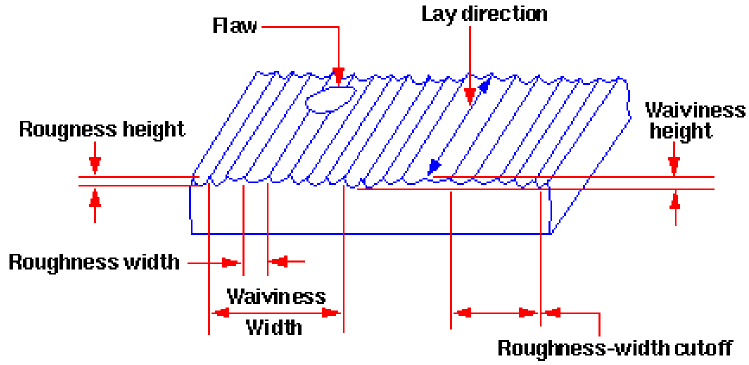


Figure 25: Surface Characteristics

The RMS value is the root mean square average of the roughness profile ordinates and can be calculated as shown below. Its numerical value is about 11% higher than that of the surface roughness value AA.

Table 4: RMS Surface Roughness

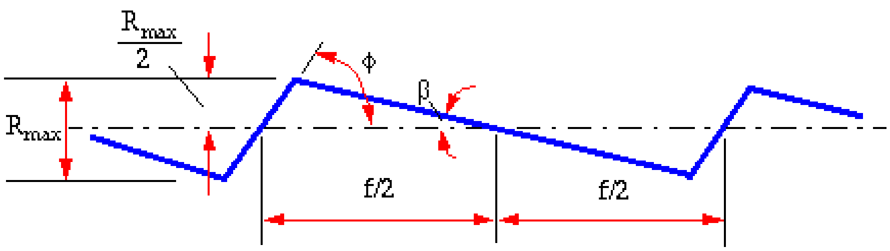
X	X^2
3	9
15	225
20	400
33	1089
25	625
18	324
5	25
10	100
15	225
15	225
5	25
11	121
14	196
13	169
27	729
8	64
Total 234	4551

AA = 234/16 = 14.6 micro in.

RMS = $(4551/16)^{1/2}$ = 16.9 micro in.

ISO Standards on Surface Finish
ISO 1302 - 2001 Indication of Surface Texture
ISO 3274 - 1996 Nominal Characteristics of Contact (Stylus) Instruments
ISO 4287 - 1997 Terms, Definition and Surface Texture Parameters
ISO 4288 - 1996 Rules and Procedures for Assessment of Surface Texture
ISO 5436-1 - 2000 Calibration, Measurement Standards
ISO 5436-2 - 2000 Calibration, Soft Gages
ISO 8785 - 1999 Surface Imperfections - Terms, Definitions and Parameters
ISO 11562 - 1996 Metrological Characteristics of Phase Correct Filters
ISO 12085 - 1996 Motif Parameters
ISO 12179 - 2000 Calibration of Contact (Stylus) Instruments
ISO 13565 - 1996 Characterization of Surfaces Having Stratified Functional Properties
Part 1 Filtering and General Measurement Conditions
Part 2 Height Characterization using the Linear Ratio Curve Conditions
Part 3 Height Characterization using the Material Probability Curve of Surfaces Consisting of Two Vertical Random Components

Ideal surface roughness represents the best possible finish for a given tool shape and feed and is a function of feed and geometry. It can be achieved only if the built-up-edge, chatter and inaccuracies in the machine tool movements are eliminated completely.



f feed

ϕ major cutting edge angle

β working minor cutting edge angle

Figure 26: Idealized Model of Surface Roughness

For a sharp tool without nose radius, the maximum height of unevenness is given by:

Equation 1

$$R_{max} = \frac{f}{\cot\phi + \cot\beta}$$

The surface roughness value is given by:

Equation 2

$$R_a = \frac{R_{max}}{4}$$

A realistic cutting tool roughness value is closely related to the feed and corner radius (r) by the following expression:

Equation 3

$$R_a = \frac{0.0321 f^2}{r}$$

Typically ideal conditions are not met and the natural surface roughness forms a large proportion of the actual roughness.

2.7Tool Chatter

Tool chatter caused by the act of machining can be detrimental to operations if not properly controlled. Excessive vibration from the tool itself decreases the surface finish of the part as well as the overall quality of the part and shortens the life of the tool. The amplitude and frequency of the vibrations from the cutting tool are directly related to the resulting surface finish. Naturally energy is transferred from the spindle to the work piece, whether it is caused by rotation or vibration. In milling the vibrations hinder the accuracy of the cutting operations because the vibrations cause the spindle to move on its axis. The lower the amplitude and frequency of the vibrations are, the less effect they have on the machining operation. Undesired vibrations also affect the accuracy of the machining operations because the excessive vibrations transferred from the machine to the work piece are not taken into consideration when the tolerances are established. This results in parts that do not meet the desired specifications with respect to dimension accuracy as well as surface finish. It is impossible to completely eliminate the vibrations caused by machining operations but measures can be taken to reduce them in order to make precision parts (Hirst, 1974; Hirst, 1974; Tabenkin, 2004).

2.7.1 Methods of Surface Finishing

There are different finishing techniques based on the specifications of the final part. The function of the surface greatly influences the method used to reduce cost and time in the process.

Surface finishing techniques include mill finish, mechanical polishing, blasting, etching, and electro-polishing. Mill finish techniques include softened and de-scaled, cold rolled, dull polished, bright polish and mirror finish. Mechanical polish produce different grit finishes from coarse to fine with a variety of degrees of smoothness. Blasting can use sand, glass or plastic to being the surfaces to a consistent appearance which eliminates the need for pre polishing and mechanical polishing. Etching Acid is commonly used for localized treatment such as welds. Electro-polishing is a process which exposes under laying material via a de-plating bath which removes the outer surface layer of the material(*0RW1S34RfeSDcfkexd09rT2Brown & sharpe, automatic screw machine handbook: Brown and sharpe speeds and feeds chart,* 1RW1S34RfeSDcfkexd09rT2).

Table 5: Speeds and Feeds Chart for a Plain HSS Tool

Cutting Speeds for Various Materials Using a Plain High Speed Steel Cutter		
Material type	**Meters per min (MPM)**	**Surface feet per min (SFM)**
Steel (tough)	15–18	50–60
Mild steel	30–38	100–125
Cast iron (medium)	18–24	60–80
Alloy steels (1320–9262)	20-37	65–120
Carbon steels (C1008-C1095)	21-40	70–130
Free cutting steels (B1111-B1113 & C1108-C1213)	35-69	115–225
Stainless steels (300 & 400 series)	23-40	75–130
Bronzes	24–45	80–150
Leaded steel (Leadloy 12L14)	91	300
Aluminum	75–105	250–350
Brass	61–91	600+ (Use the maximum spindle speed)

(Brown & Sharpe,)(*0RW1S34RfeSDcfkexd09rT2Brown & sharpe, automatic screw machine handbook: Brown and sharpe speeds and feeds chart,* 1RW1S34RfeSDcfkexd09rT2)

2.8 Computer Aided Design and Manufacturing

2.8.1 Computer Aided Design (CAD)

Computer Aided Design, often abbreviated in the engineering field as CAD, has become an integral part of machining. CAD technologies allow engineers to accurately create three dimensional digital models of parts they are interested in manufacturing. This allows engineers to easily visualize and assemble multiple parts without going through the expensive process of prototyping. Since its invention CAD has become fundamental in design, drafting, and analysis. There are many varieties of CAD software available to engineers and machinists. The simplest programs allow the operator to create a simple two dimensional drawing; essentially no different from a hand drawn engineering drawing. The more complex programs however are able to create and model intricate assemblies as well as perform accurate heat and stress analyses. At Worcester Polytechnic Institute (WPI) students have access to primarily to the Pro Engineer and Solid Works programs (Oberg et al., 2000).

2.8.2 Computer Aided Manufacturing (CAM)

Computer Aided Machining, or CAM, is used to help machinists and engineers simulate the required tool paths to create a part. CAM is often interfaced with design software and CAD programs so that solid models can easily be transferred between programs. This allows an engineer to create his or her model in CAD and then send it to a CAM program to set up tool paths. The other useful ability that is available with CAM is that it can quickly create tool paths in NC code. Once and engineer or machinist has the tool paths drawn and visualized in the CAM program usually he or she is able to directly transfer the information into the CNC machine. CAM allows someone with very limited knowledge of NC code to easily machine very complex parts. The CAM program that is most often used at WPI is Esprit(Oberg et al., 2000).

2.9 Design for Manufacturability

There are hundreds of factors that need to be accounted for when manufacturing a part. These factors all affect some aspect of the part, from surface finish to material type, but no other factor in the process has a greater impact on the entire process from beginning to end than the design of the part. The design of a part is the single greatest influential factor when it comes to actually machine it. A complex part can cost hundreds of dollars to machine while a simple one may be a few dollars. The contributing factors to cost are important to consider when designing a part because the product needs to be sold at a profit. The concept of making a part no more complex than it needs to be and lowering the cost of machining is a simple one, but important for and mechanical or manufacturing engineer.

With the development of modern machine tools and more advanced capabilities of those machine tools the way parts and processes are designed has shifted. A development in the past 20 years has been the new model of design, design for manufacturability. The idea is to anticipate and avoid problematic aspects of assembly, fabrication, test, etc. all the while assuring the best quality and reliability (David M Anderson, 2004 CIM Press). Once a revolutionary concept, design for manufacturability (DFM), has now been universally adopted as the best way to improve concept to product times while maintaining reliability and low cost (Engineers Edge,). Any company or person who want to shorten product development times, costs, and time to market should stronger consider the use of DFM as the method used to achieve all these goals.

The basics of DFM are generally applied in a group setting to gain a greater scope of skills and abilities due to how design for manufacturability is based upon the experience of those performing it. The persons need to know manufacturing and the limitations inherent in each process of machining to keep the design within the realm of possibility. Most parts are going to be produced from standard manufacturing processes, but if they are not then the new process should be concurrently designed (David M Anderson, 2004 CIM Press). The design team must have the mind set of working with all others on all aspects to gain the necessary advice from and experienced person in that field, this includes even people from marketing and finance that will have to sell and promote the product. This is a drastic step away from the old method of one person designing the part or product and then sending it to another department to be manufactured (Engineers Edge,).

Chapter 3

3.1 Our progression

This project was intended to allow the group members to become proficient in all areas of CNC machining and become specialists in the manufacturing field. Our goal was to, when given a part, be able to create it using CAD and CAM software and then manufacture it. Initially no member of the group had experience in all disciplines required of a manufacturing engineer. Each group member possessed some of the skills necessary to actively machine parts; however no one had ability to do it independently.

During the first two months the group set guidelines and goals that would ensure proficiency in machining disciplines. The early months were dedicated to background research, allowing the group to establish greater knowledge of manufacturing. This period of research helped us understand the necessary terminology, general machining operations, and technological advances that propel the industry. We compiled our research and it was later used as material for chapter 1. We also focused on refreshing our skills with CAD software. We all had previously taken a CAD course, but we needed to practice and hone our skills to be able to create complex parts and assemblies.

The next two months were also a learning period for the group. After mastering CAD software we needed to develop proficiency with Computer Aided Manufacturing (CAM) software so that the programs could then be used in the machine to manufacture parts. We taught ourselves how to use the CAM program Esprit by following tutorials and through experimentation. We used the CAD models we had created, imported them into Esprit and then systematically figured out how to apply appropriate machining operations. We learned how to determine the required speed and feed rates, as well as specify other important values such as incremental depth. We also began developing proficiency using CNC machines. Some of the group members had previously taken a basic manufacturing course, but were not educated or skilled enough to perform operations on their own. Under the instruction of a lab monitor, we spent a great deal of time learning the proper procedures and how to conduct safe operations in the Machine shop. Our focus was learning to use the Haas mini mill. We learned how to transfer the Numerical Control code (NC code) from Esprit to the machine, probe the cutting tools and the work piece, and the rest of the steps to machine a part. We were taught how to perform pocketing, facing, and drilling operations. After being taught the basics of machining, we practiced frequently and hone our skills.

With a solid base of machining knowledge established we began to create unique and complex parts, as well as analyze the process of machining. It was during this period we accomplished the majority of the work necessary to achieve the goals we developed at the beginning of the project and write our report. Through further practice and experimentation we were able to make detailed analyses consisting of entire process required to manufacture parts. It was during this period that all of our group members completed the goal of becoming proficient in all areas of machining. We extended our project an additional two months to give us ample time to produce a good report.

3.2 Drill part

During the middle months we experimented with several types of fits. We drilled holes of all different depths and diameters into 6061 aluminum alloy stock. We create numerous parts with holes drilled holes every inch to maximize the fit experiments we could perform on each piece of stock. We acquired several metal dowels that were available in the machine shop, decided what types of fits we wanted to create, and then we selected the drill bits we necessary to create the proper hole sizes. The CAM model for one such experiment is pictured in Figure 27.

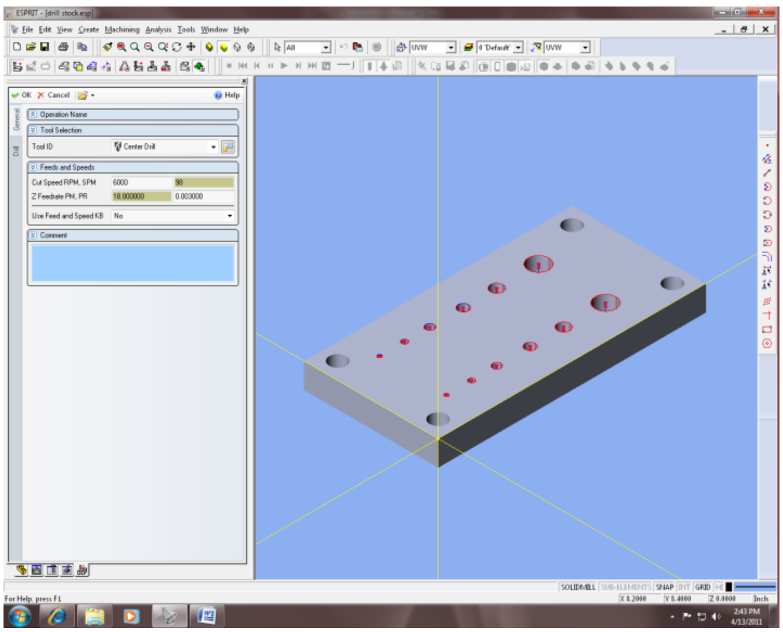


Figure 27: Demonstration piece that show tolerance in drilling

With 8” x 4” x 1.5”stock we created a piece that was able to demonstrate several types of fits. For this experiment we drilled 12 holes ranging in size from 0.125” diameter to 0.625” diameter. The holes were situated on the work piece so that one side was intended for entirely force fits and the other for entirely slip fits. We chose the size of the holes with respect to the dowels we had available. We decided what type of fits we wanted to create and then selected the appropriate drill bit diameter.

This program had several operations involved. Using a 0.0625" center drill we taped all twelve holes. Each tap hole had a depth on 0.1". This provided a start for each of the other drills greatly increasing the precision of the hole locations. We then created the drill operations and set suitable speed and feed rates. The speed and feed rates we used are listed in Figure 5. This table shows the tool name and underneath it, the cutting rates.

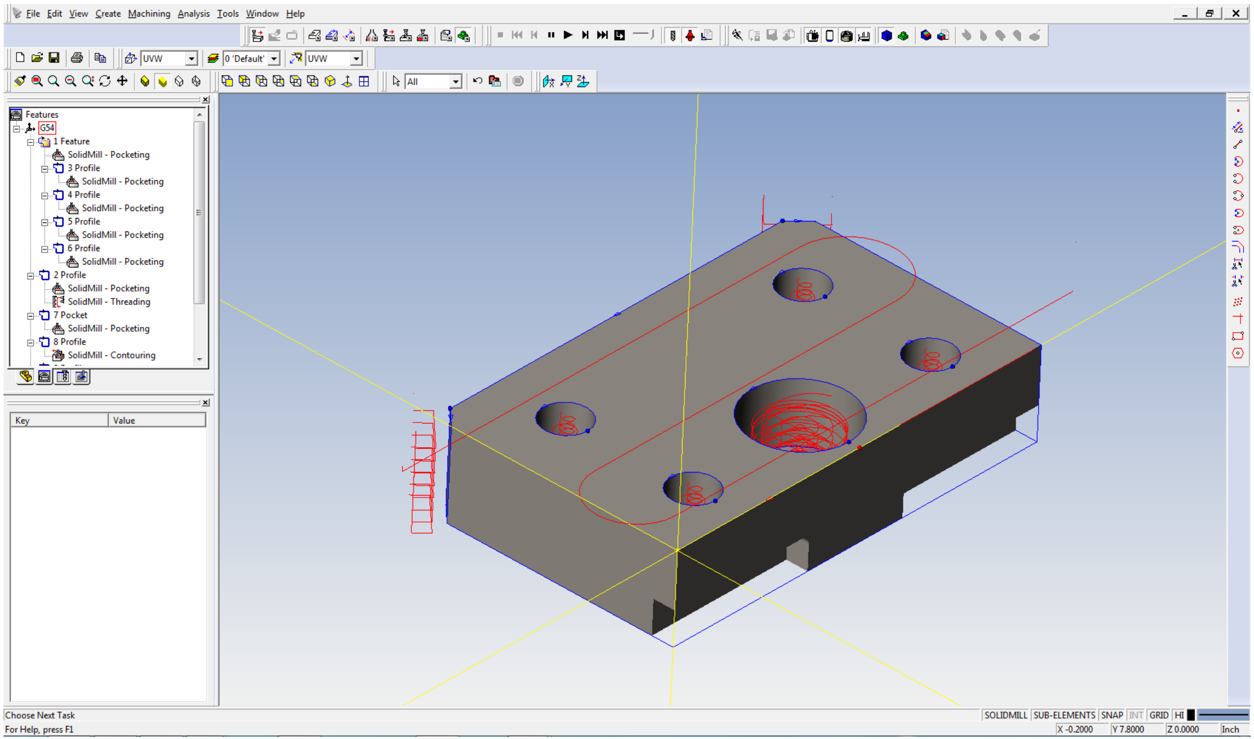
We ran into restrictions with the limitations of the Mini Mill we were using. Unlike the larger VM3 and VM4 machines the Mini Mill is only able to carry 10 tools at a time. This became a problem since our part called for 12 holes and a spot drill. Therefore in order to run the operation we were forced to stop the machine and switch tools. We also had to suppress certain operations in the program depending on what tools were loaded into the machine. Suppressing some of the operations allowed us to drill only a few holes at a time. We then changed the tools in the machine and suppressed other operations and then finished drilling all the holes. When we ran the program in the machine we used coolant to prevent the cutting tool from overheating. The entire machining process, including changing the tools and altering the CAM program took approximately 18 minutes.

The first time we ran this drilling operation we encountered several problems. The first was that during tapping we kept drilling too deep. Instead of the prescribed 0.1 inch spot drill, we were drilling at closer to 0.2 inches. While this was not a major problem in the initial drilling, were we to do a more precise part, we may have been off on the tolerances of our holes. In most machining applications when a hole is drilled the operator usually includes an initial spot drill to help increase the accuracy of the hole. In our case we used a drill mill rather than a spot drill; this may have resulted in the 0.2 inch error in our initial operation.

Another problem we had was during the tool's approach to the work piece. When we began to drill a hole, the tool would begin pecking much further from the piece than expected. This is an error with the esprit program we created. This meant that the time to drill took much longer than it should have. This greatly slowed the machining process.

3.3 Flange

Besides experimenting with types of fits and surface finishes, we also machined several specific parts, including a flange from Siemens. The flange was the last part we machined and had to be manufactured to exact specifications. We were given the engineering drawings from the company and then put the model into our CAD software (SolidWorks). Once that was finished we then transfer the model from CAD into our CAM software (Esprit). In Esprit we created several features that would generate the NC code necessary to machine the part. First, we created 7 pocketing operations in order to mill the 5 holes and the 2 rectangular open-faced pockets. We then made a threading feature for the largest pocket and also made a contouring feature to round off the 2 corners. The last feature we created was a facing operation in order to give the part a nice smooth surface finish. We researched and selected the appropriate speed and feed rates for each individual operation as well as the suitable incremental depths and other important values. Once these values were set and the tooling was selected we were ready to machine the part.



To machine this part we used a HAAS mini mill and 3 different cutting tools. The main tool used was the ½ inch end mill. This was used for all the pocketing and contouring operations. The other two tools we used were the 7/8-14 thread mill and the 3 inch face mill. These tools were all loaded into the machine at once but we had to suppress some of the operations because the part had to be repositioned in order to machine all the features. We used 6061 aluminum alloy for this part. After machining the part and checking the dimensions we concluded that the part met all the specifications the engineering drawings required.

Chapter 4: Concluding Remarks

With the current economic conditions and United States machining and manufacturing contracts continually being awarded to overseas companies there is an extreme need for talented and knowledgeable individuals to join the manufacturing industry. As the economy of outsourcing manufacturing and assembly of products to Southeast Asia becomes less of an advantage, due to factors such as rising fuel and transportation costs, manufacturing may and has already begun to return to the United States. With the advances in technology and advanced processes the idea of the U.S. becoming the production and manufacturing powerhouse of the world again becomes more of a realization than an idea. This project was a combination of researching the factors that affect a machining operation and how to minimize negative effects on production while trying to personally ascertain skills that will help the manufacturing industry stay on the cutting edge and keep manufacturing in the country.

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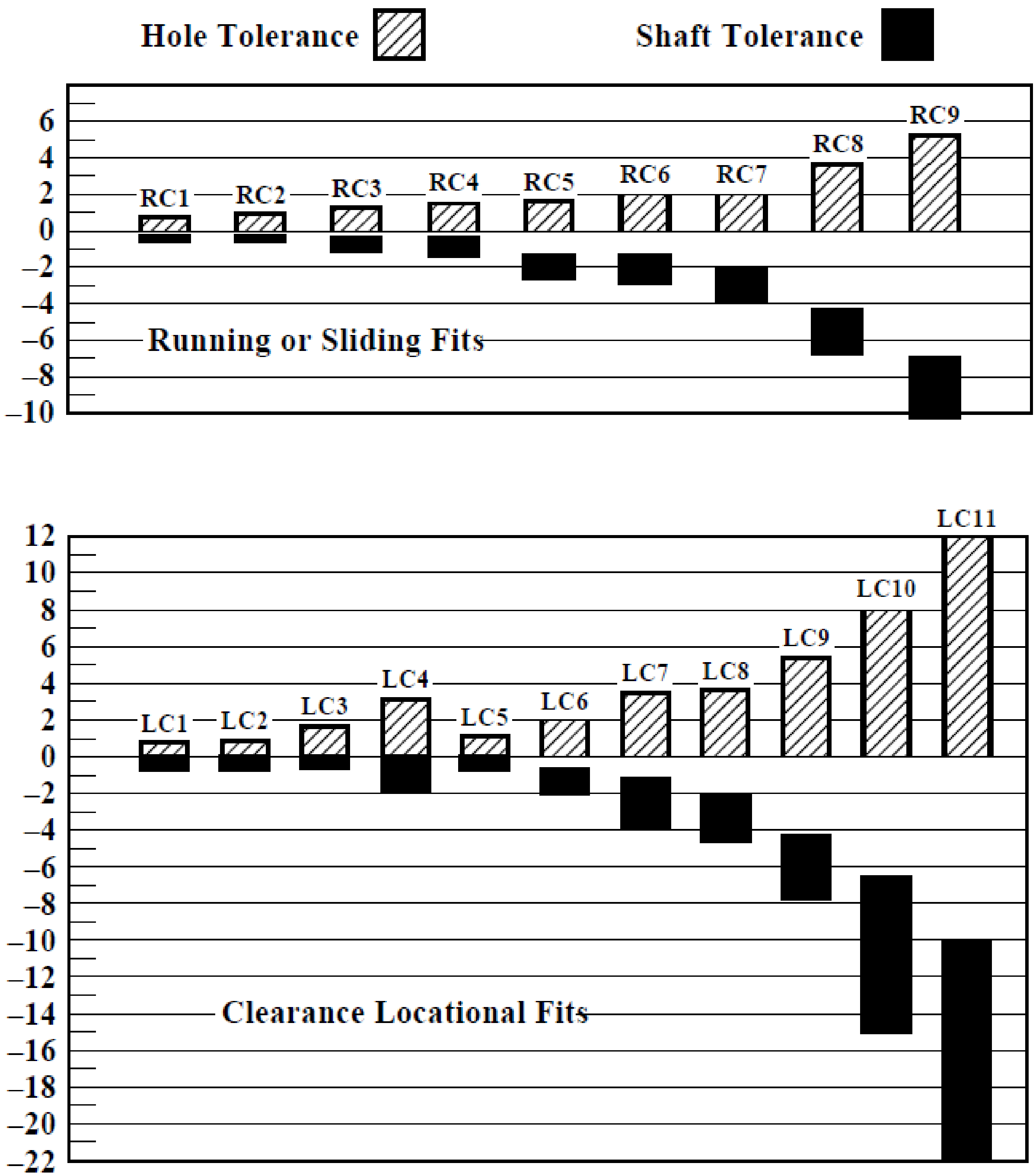
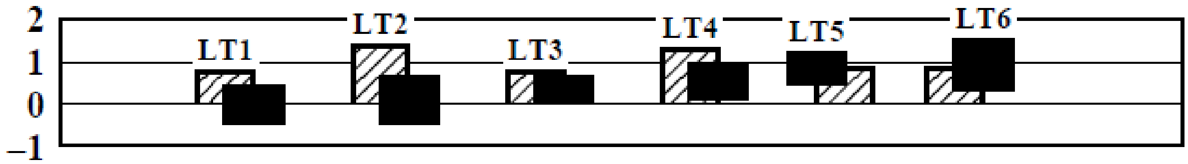
Appendix A

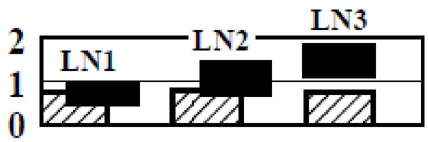
Standards and Tables for Fits

Graphical Representation of ANSI Standard Limits and Fits

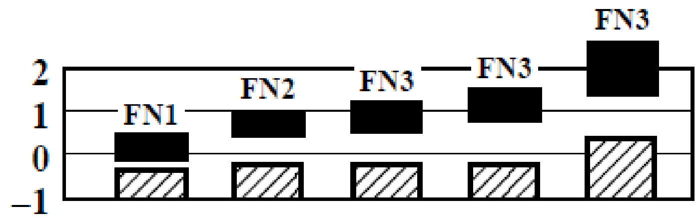




Transition Fits



Interference Locational Fits



Force or Shrink Fits

Nominal Size Range, Inches	Class RC 1			Class RC 2			Class RC 3			Class RC 4		
	Clear-ance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits	
		Hole H5	Shaft g4		Hole H6	Shaft g5		Hole H7	Shaft f6		Hole H8	Shaft f7
Over To	Values shown below are in thousandths of an inch											
0 – 0.12	0.1 0.45	+0.2 0	–0.1 –0.25	0.1 0.55	+0.25 0	–0.1 –0.3	0.3 0.95	+0.4 0	–0.3 –0.55	0.3 1.3	+0.6 0	–0.3 –0.7
0.12 – 0.24	0.15 0.5	+0.2 0	–0.15 –0.3	0.15 0.65	+0.3 0	–0.15 –0.35	0.4 1.12	+0.5 0	–0.4 –0.7	0.4 1.6	+0.7 0	–0.4 –0.9
0.24 – 0.40	0.2 0.6	+0.25 0	–0.2 –0.35	0.2 0.85	+0.4 0	–0.2 –0.45	0.5 1.5	+0.6 0	–0.5 –0.9	0.5 2.0	+0.9 0	–0.5 –1.1
0.40 – 0.71	0.25 0.75	+0.3 0	–0.25 –0.45	0.25 0.95	+0.4 0	–0.25 –0.55	0.6 1.7	+0.7 0	–0.6 –1.0	0.6 2.3	+1.0 0	–0.6 –1.3
0.71 – 1.19	0.3 0.95	+0.4 0	–0.3 –0.55	0.3 1.2	+0.5 0	–0.3 –0.7	0.8 2.1	+0.8 0	–0.8 –1.3	0.8 2.8	+1.2 0	–0.8 –1.6
1.19 – 1.97	0.4 1.1	+0.4 0	–0.4 –0.7	0.4 1.4	+0.6 0	–0.4 –0.8	1.0 2.6	+1.0 0	–1.0 –1.6	1.0 3.6	+1.6 0	–1.0 –2.0
1.97 – 3.15	0.4 1.2	+0.5 0	–0.4 –0.7	0.4 1.6	+0.7 0	–0.4 –0.9	1.2 3.1	+1.2 0	–1.2 –1.9	1.2 4.2	+1.8 0	–1.2 –2.4
3.15 – 4.73	0.5 1.5	+0.6 0	–0.5 –0.9	0.5 2.0	+0.9 0	–0.5 –1.1	1.4 3.7	+1.4 0	–1.4 –2.3	1.4 5.0	+2.2 0	–1.4 –2.8
4.73 – 7.09	0.6 1.8	+0.7 0	–0.6 –1.1	0.6 2.3	+1.0 0	–0.6 –1.3	1.6 4.2	+1.6 0	–1.6 –2.6	1.6 5.7	+2.5 0	–1.6 –3.2
7.09 – 9.85	0.6 2.0	+0.8 0	–0.6 –1.2	0.6 2.6	+1.2 0	–0.6 –1.4	2.0 5.0	+1.8 0	–2.0 –3.2	2.0 6.6	+2.8 0	–2.0 –3.8
9.85 – 12.41	0.8 2.3	+0.9 0	–0.8 –1.4	0.8 2.9	+1.2 0	–0.8 –1.7	2.5 5.7	+2.0 0	–2.5 –3.7	2.5 7.5	+3.0 0	–2.5 –4.5
12.41 – 15.75	1.0 2.7	+1.0 0	–1.0 –1.7	1.0 3.4	+1.4 0	–1.0 –2.0	3.0 6.6	+2.2 0	–3.0 –4.4	3.0 8.7	+3.5 0	–3.0 –5.2
15.75 – 19.69	1.2 3.0	+1.0 0	–1.2 –2.0	1.2 3.8	+1.6 0	–1.2 –2.2	4.0 8.1	+2.5 0	–4.0 –5.6	4.0 10.5	+4.0 0	–4.0 –6.5

Table 4. American National Standard Running and Sliding Fits *ANSI B4.1-1967 (R1987)*

Nominal Size Range, Inches	Class RC 5			Class RC 6			Class RC 7			Class RC 8			Class RC 9		
		Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits	
Over To	Clearance[a]	Hole H8	Shaft e7	Clearance[a]	Hole H9	Shaft e8	Clearance[a]	Hole H9	Shaft d8	Clearance[a]	Hole H10	Shaft c9	Clearance[a]	Hole H11	Shaft
	Values shown below are in thousandths of an inch														
0 – 0.12	0.6 1.6	+0.6 0	− 0.6 − 1.0	0.6 2.2	+1.0 0	− 0.6 − 1.2	1.0 2.6	+1.0 0	− 1.0 − 1.6	2.5 5.1	+1.6 0	− 2.5 − 3.5	4.0 8.1	+2.5 0	− 4.0 − 5.6
0.12 – 0.24	0.8 2.0	+0.7 0	− 0.8 − 1.3	0.8 2.7	+1.2 0	− 0.8 − 1.5	1.2 3.1	+1.2 0	− 1.2 − 1.9	2.8 5.8	+1.8 0	− 2.8 − 4.0	4.5 9.0	+3.0 0	− 4.5 − 6.0
0.24 – 0.40	1.0 2.5	+0.9 0	− 1.0 − 1.6	1.0 3.3	+1.4 0	− 1.0 − 1.9	1.6 3.9	+1.4 0	− 1.6 − 2.5	3.0 6.6	+2.2 0	− 3.0 − 4.4	5.0 10.7	+3.5 0	− 5.0 − 7.2
0.40 – 0.71	1.2 2.9	+1.0 0	− 1.2 − 1.9	1.2 3.8	+1.6 0	− 1.2 − 2.2	2.0 4.6	+1.6 0	− 2.0 − 3.0	3.5 7.9	+2.8 0	− 3.5 − 5.1	6.0 12.8	+4.0 0	− 6.0 − 8.8
0.71 – 1.19	1.6 3.6	+1.2 0	− 1.6 − 2.4	1.6 4.8	+2.0 0	− 1.6 − 2.8	2.5 5.7	+2.0 0	− 2.5 − 3.7	4.5 10.0	+3.5 0	− 4.5 − 6.5	7.0 15.5	+5.0 0	− 7.0 −10.5
1.19 – 1.97	2.0 4.6	+1.6 0	− 2.0 − 3.0	2.0 6.1	+2.5 0	− 2.0 − 3.6	3.0 7.1	+2.5 0	− 3.0 − 4.6	5.0 11.5	+4.0 0	− 5.0 − 7.5	8.0 18.0	+6.0 0	− 8.0 −12.0
1.97 – 3.15	2.5 5.5	+1.8 0	− 2.5 − 3.7	2.5 7.3	+3.0 0	− 2.5 − 4.3	4.0 8.8	+3.0 0	− 4.0 − 5.8	6.0 13.5	+4.5 0	− 6.0 − 9.0	9.0 20.5	+7.0 0	− 9.0 −13.5
3.15 – 4.73	3.0 6.6	+2.2 0	− 3.0 − 4.4	3.0 8.7	+3.5 0	− 3.0 − 5.2	5.0 10.7	+3.5 0	− 5.0 − 7.2	7.0 15.5	+5.0 0	− 7.0 −10.5	10.0 24.0	+9.0 0	−10.0 −15.0
4.73 – 7.09	3.5 7.6	+2.5 0	− 3.5 − 5.1	3.5 10.0	+4.0 0	− 3.5 − 6.0	6.0 12.5	+4.0 0	− 6.0 − 8.5	8.0 18.0	+6.0 0	− 8.0 −12.0	12.0 28.0	+10.0 0	−12.0 −18.0
7.09 – 9.85	4.0 8.6	+2.8 0	− 4.0 − 5.8	4.0 11.3	+4.5 0	− 4.0 − 6.8	7.0 14.3	+4.5 0	− 7.0 − 9.8	10.0 21.5	+7.0 0	−10.0 −14.5	15.0 34.0	+12.0 0	−15.0 −22.0
9.85 – 12.41	5.0 10.0	+3.0 0	− 5.0 − 7.0	5.0 13.0	+5.0 0	− 5.0 − 8.0	8.0 16.0	+5.0 0	− 8.0 −11.0	12.0 25.0	+8.0 0	−12.0 −17.0	18.0 38.0	+12.0 0	−18.0 −26.0
12.41 – 15.75	6.0 11.7	+3.5 0	− 6.0 − 8.2	6.0 15.5	+6.0 0	− 6.0 − 9.5	10.0 19.5	+6.0 0	−10.0 −13.5	14.0 29.0	+9.0 0	−14.0 −20.0	22.0 45.0	+14.0 0	−22.0 −31.0
15.75 – 19.69	8.0 14.5	+4.0 0	− 8.0 −10.5	8.0 18.0	+6.0 0	− 8.0 −12.0	12.0 22.0	+6.0 0	−12.0 −16.0	16.0 32.0	+10.0 0	−16.0 −22.0	25.0 51.0	+16.0 0	−25.0 −35.0

Table 5. American National Standard Clearance Locational Fits *ANSI B4.1-1967 (R1987)*

Nominal Size Range, Inches	Class LC 1			Class LC 2			Class LC 3			Class LC 4			Class LC 5		
		Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits	
Over To	Clearance[a]	Hole H6	Shaft h5	Clearance[a]	Hole H7	Shaft h6	Clearance[a]	Hole H8	Shaft h7	Clearance[a]	Hole H10	Shaft h9	Clearance[a]	Hole H7	Shaft g6
	Values shown below are in thousandths of an inch														
0– 0.12	0 0.45	+0.25 0	0 −0.2	0 0.65	+0.4 0	0 −0.25	0 1	+0.6 0	0 −0.4	0 2.6	+1.6 0	0 −1.0	0.1 0.75	+0.4 0	−0.1 −0.35
0.12– 0.24	0 0.5	+0.3 0	0 −0.2	0 0.8	+0.5 0	0 −0.3	0 1.2	+0.7 0	0 −0.5	0 3.0	+1.8 0	0 −1.2	0.15 0.95	+0.5 0	−0.15 −0.45
0.24– 0.40	0 0.65	+0.4 0	0 −0.25	0 1.0	+0.6 0	0 −0.4	0 1.5	+0.9 0	0 −0.6	0 3.6	+2.2 0	0 −1.4	0.2 1.2	+0.6 0	−0.2 −0.6
0.40– 0.71	0 0.7	+0.4 0	0 −0.3	0 1.1	+0.7 0	0 −0.4	0 1.7	+1.0 0	0 −0.7	0 4.4	+2.8 0	0 −1.6	0.25 1.35	+0.7 0	−0.25 −0.65
0.71– 1.19	0 0.9	+0.5 0	0 −0.4	0 1.3	+0.8 0	0 −0.5	0 2	+1.2 0	0 −0.8	0 5.5	+3.5 0	0 −2.0	0.3 1.6	+0.8 0	−0.3 −0.8
1.19– 1.97	0 1.0	+0.6 0	0 −0.4	0 1.6	+1.0 0	0 −0.6	0 2.6	+1.6 0	0 −1	0 6.5	+4.0 0	0 −2.5	0.4 2.0	+1.0 0	−0.4 −1.0
1.97– 3.15	0 1.2	+0.7 0	0 −0.5	0 1.9	+1.2 0	0 −0.7	0 3	+1.8 0	0 −1.2	0 7.5	+4.5 0	0 −3	0.4 2.3	+1.2 0	−0.4 −1.1
3.15– 4.73	0 1.5	+0.9 0	0 −0.6	0 2.3	+1.4 0	0 −0.9	0 3.6	+2.2 0	0 −1.4	0 8.5	+5.0 0	0 −3.5	0.5 2.8	+1.4 0	−0.5 −1.4
4.73– 7.09	0 1.7	+1.0 0	0 −0.7	0 2.6	+1.6 0	0 −1.0	0 4.1	+2.5 0	0 −1.6	0 10.0	+6.0 0	0 −4	0.6 3.2	+1.6 0	−0.6 −1.6
7.09– 9.85	0 2.0	+1.2 0	0 −0.8	0 3.0	+1.8 0	0 −1.2	0 4.6	+2.8 0	0 −1.8	0 11.5	+7.0 0	0 −4.5	0.6 3.6	+1.8 0	−0.6 −1.8
9.85– 12.41	0 2.1	+1.2 0	0 −0.9	0 3.2	+2.0 0	0 −1.2	0 5	+3.0 0	0 −2.0	0 13.0	+8.0 0	0 −5	0.7 3.9	+2.0 0	−0.7 −1.9
12.41– 15.75	0 2.4	+1.4 0	0 −1.0	0 3.6	+2.2 0	0 −1.4	0 5.7	+3.5 0	0 −2.2	0 15.0	+9.0 0	0 −6	0.7 4.3	+2.2 0	−0.7 −2.1
15.75– 19.69	0 2.6	+1.6 0	0 −1.0	0 4.1	+2.5 0	0 −1.6	0 6.5	+4 0	0 −2.5	0 16.0	+10.0 0	0 −6	0.8 4.9	+2.5 0	−0.8 −2.4

ALLOWANCES AND TOLERANCES

Table 6. American National Standard Clearance Locational Fits *ANSI B4.1-1967 (R1987)*

Nominal Size Range, Inches	Class LC 6			Class LC 7			Class LC 8			Class LC 9			Class LC 10			Class LC 11		
		Std. Tolerance Limits			Std. Tolerance Limits			Std. Tolerance Limits			Std. Tolerance Limits			Std. Tolerance Limits			Std. Tolerance Limits	
Over – To	Clearance[a]	Hole H9	Shaft f8	Clearance[a]	Hole H10	Shaft e9	Clearance[a]	Hole H10	Shaft d9	Clearance[a]	Hole H11	Shaft c10	Clearance[a]	Hole H12	Shaft	Clearance[a]	Hole H13	Shaft
	Values shown below are in thousandths of an inch																	
0 – 0.12	0.3 1.9	+1.0 0	−0.3 −0.9	0.6 3.2	+1.6 0	− 0.6 − 1.6	1.0 2.0	+1.6 0	− 1.0 − 2.0	2.5 6.6	+2.5 0	− 2.5 − 4.1	4 12	+4 0	− 4 − 8	5 17	+6 0	− 5 − 11
0.12 – 0.24	0.4 2.3	+1.2 0	−0.4 −1.1	0.8 3.8	+1.8 0	− 0.8 − 2.0	1.2 4.2	+1.8 0	− 1.2 − 2.4	2.8 7.6	+3.0 0	− 2.8 − 4.6	4.5 14.5	+5 0	− 4.5 − 9.5	6 20	+7 0	− 6 −13
0.24 – 0.40	0.5 2.8	+1.4 0	−0.5 −1.4	1.0 4.6	+2.2 0	− 1.0 − 2.4	1.6 5.2	+2.2 0	− 1.6 − 3.0	3.0 8.7	+3.5 0	− 3.0 − 5.2	5 17	+6 0	− 5 −11	7 25	+9 0	− 7 −16
0.40 – 0.71	0.6 3.2	+1.6 0	−0.6 −1.6	1.2 5.6	+2.8 0	− 1.2 − 2.8	2.0 6.4	+2.8 0	− 2.0 − 3.6	3.5 10.3	+4.0 0	− 3.5 − 6.3	6 20	+7 0	− 6 −13	8 28	+10 0	− 8 −18
0.71 – 1.19	0.8 4.0	+2.0 0	−0.8 −2.0	1.6 7.1	+3.5 0	− 1.6 − 3.6	2.5 8.0	+3.5 0	− 2.5 − 4.5	4.5 13.0	+5.0 0	− 4.5 − 8.0	7 23	+8 0	− 7 −15	10 34	+12 0	−10 −22
1.19 – 1.97	1.0 5.1	+2.5 0	−1.0 −2.6	2.0 8.5	+4.0 0	− 2.0 − 4.5	3.6 9.5	+4.0 0	− 3.0 − 5.5	5.0 15.0	+6 0	− 5.0 − 9.0	8 28	+10 0	− 8 −18	12 44	+16 0	−12 −28
1.97 – 3.15	1.2 6.0	+3.0 0	−1.0 −3.0	2.5 10.0	+4.5 0	− 2.5 − 5.5	4.0 11.5	+4.5 0	− 4.0 − 7.0	6.0 17.5	+7 0	− 6.0 −10.5	10 34	+12 0	−10 −22	14 50	+18 0	−14 −32
3.15 – 4.73	1.4 7.1	+3.5 0	−1.4 −3.6	3.0 11.5	+5.0 0	− 3.0 − 6.5	5.0 13.5	+5.0 0	− 5.0 − 8.5	7 21	+9 0	− 7 −12	11 39	+14 0	−11 −25	16 60	+22 0	−16 −38
4.73 – 7.09	1.6 8.1	+4.0 0	−1.6 −4.1	3.5 13.5	+6.0 0	− 3.5 − 7.5	6 16	+6 0	− 6 −10	8 24	+10 0	− 8 −14	12 44	+16 0	−12 −28	18 68	+25 0	−18 −43
7.09 – 9.85	2.0 9.3	+4.5 0	−2.0 −4.8	4.0 15.5	+7.0 0	− 4.0 − 8.5	7 18.5	+7 0	− 7 −11.5	10 29	+12 0	−10 −17	16 52	+18 0	−16 −34	22 78	+28 0	−22 −50
9.85 – 12.41	2.2 10.2	+5.0 0	−2.2 −5.2	4.5 17.5	+8.0 0	− 4.5 − 9.5	7 20	+8 0	− 7 −12	12 32	+12 0	−12 −20	20 60	+20 0	−20 −40	28 88	+30 0	−28 −58
12.41 – 15.75	2.5 12.0	+6.0 0	−2.5 −6.0	5.0 20.0	+9.0 0	− 5 −11	8 23	+9 0	− 8 −14	14 37	+14 0	−14 −23	22 66	+22 0	−22 −44	30 100	+35 0	−30 −65
15.75 – 19.69	2.8 12.8	+6.0 0	−2.8 −6.8	5.0 21.0	+10.0 0	− 5 −11	9 25	+10 0	− 9 −15	16 42	+16 0	−16 −26	25 75	+25 0	−25 −50	35 115	+40 0	−35 −75

Table 7. ANSI Standard Transition Locational Fits *ANSI B4.1-1967 (R1987)*

Nominal Size Range, Inches	Class LT 1			Class LT 2			Class LT 3			Class LT 4			Class LT 5			Class LT 6		
		Std. Tolerance Limits			Std. Tolerance Limits			Std. Tolerance Limits			Std. Tolerance Limits			Std. Tolerance Limits			Std. Tolerance Limits	
Over – To	Fit[a]	Hole H7	Shaft js6	Fit[a]	Hole H8	Shaft js7	Fit[a]	Hole H7	Shaft k6	Fit[a]	Hole H8	Shaft k7	Fit[a]	Hole H7	Shaft n6	Fit[a]	Hole H7	Shaft n7
	Values shown below are in thousandths of an inch																	
0 – 0.12	−0.12 +0.52	+0.4 0	+0.12 −0.12	−0.2 +0.8	+0.6 0	+0.2 −0.2							−0.5 +0.15	+0.4 0	+0.5 +0.25	−0.65 +0.15	+0.4 0	+0.65 +0.25
0.12 – 0.24	−0.15 +0.65	+0.5 0	+0.15 −0.15	−0.25 +0.95	+0.7 0	+0.25 −0.25							−0.6 +0.2	+0.5 0	+0.6 +0.3	−0.8 +0.2	+0.5 0	+0.8 +0.3
0.24 – 0.40	−0.2 +0.8	+0.6 0	+0.2 −0.2	−0.3 +1.2	+0.9 0	+0.3 −0.3	−0.5 +0.5	+0.6 0	+0.5 +0.1	−0.7 +0.8	+0.9 0	+0.7 +0.1	−0.8 +0.2	+0.6 0	+0.8 +0.4	−1.0 +0.2	+0.6 0	+1.0 +0.4
0.40 – 0.71	−0.2 +0.9	+0.7 0	+0.2 −0.2	−0.35 +1.35	+1.0 0	+0.35 −0.35	−0.5 +0.6	+0.7 0	+0.5 +0.1	−0.8 +0.9	+1.0 0	+0.8 +0.1	−0.9 +0.2	+0.7 0	+0.9 +0.5	−1.2 +0.2	+0.7 0	+1.2 +0.5
0.71 – 1.19	−0.25 +1.05	+0.8 0	+0.25 −0.25	−0.4 +1.6	+1.2 0	+0.4 −0.4	−0.6 +0.7	+0.8 0	+0.6 +0.1	−0.9 +1.1	+1.2 0	+0.9 +0.1	−1.1 +0.2	+0.8 0	+1.1 +0.6	−1.4 +0.2	+0.8 0	+1.4 +0.6
1.19 – 1.97	−0.3 +1.3	+1.0 0	+0.3 −0.3	−0.5 +2.1	+1.6 0	+0.5 −0.5	−0.7 +0.9	+1.0 0	+0.7 +0.1	−1.1 +1.5	+1.6 0	+1.1 +0.1	−1.3 +0.3	+1.0 0	+1.3 +0.7	−1.7 +0.3	+1.0 0	+1.7 +0.7
1.97 – 3.15	−0.3 +1.5	+1.2 0	+0.3 −0.3	−0.6 +2.4	+1.8 0	+0.6 −0.6	−0.8 +1.1	+1.2 0	+0.8 +0.1	−1.3 +1.7	+1.8 0	+1.3 +0.1	−1.5 +0.4	+1.2 0	+1.5 +0.8	−2.0 +0.4	+1.2 0	+2.0 +0.8
3.15 – 4.73	−0.4 +1.8	+1.4 0	+0.4 −0.4	−0.7 +2.9	+2.2 0	+0.7 −0.7	−1.0 +1.3	+1.4 0	+1.0 +0.1	−1.5 +2.1	+2.2 0	+1.5 +0.1	−1.9 +0.4	+1.4 0	+1.9 +1.0	−2.4 +0.4	+1.4 0	+2.4 +1.0
4.73 – 7.09	−0.5 +2.1	+1.6 0	+0.5 −0.5	−0.8 +3.3	+2.5 0	+0.8 −0.8	−1.1 +1.5	+1.6 0	+1.1 +0.1	−1.7 +2.4	+2.5 0	+1.7 +0.1	−2.2 +0.4	+1.6 0	+2.2 +1.2	−2.8 +0.4	+1.6 0	+2.8 +1.2
7.09 – 9.85	−0.6 +2.4	+1.8 0	+0.6 −0.6	−0.9 +3.7	+2.8 0	+0.9 −0.9	−1.4 +1.6	+1.8 0	+1.4 +0.2	−2.0 +2.6	+2.8 0	+2.0 +0.2	−2.6 +0.4	+1.8 0	+2.6 +1.4	−3.2 +0.4	+1.8 0	+3.2 +1.4
9.85 – 12.41	−0.6 +2.6	+2.0 0	+0.6 −6.6	−1.0 +4.0	+3.0 0	+1.0 −1.0	−1.4 +1.8	+2.0 0	+1.4 +0.2	−2.2 +2.8	+3.0 0	+2.2 +0.2	−2.6 +0.6	+2.0 0	+2.6 +1.4	−3.4 +0.6	+2.0 0	+3.4 +1.4
12.41 – 15.75	−0.7 +2.9	+2.2 0	+0.7 −0.7	−1.0 +4.5	+3.5 0	+1.0 −1.0	−1.6 +2.0	+2.2 0	+1.6 +0.2	−2.4 +3.3	+3.5 0	+2.4 +0.2	−3.0 +0.6	+2.2 0	+3.0 +1.6	−3.8 +0.6	+2.2 0	+3.8 +1.6
15.75 – 19.69	−0.8 +3.3	+2.5 0	+0.8 −0.8	−1.2 +5.2	+4.0 0	+1.2 −1.2	−1.8 +2.3	+2.5 0	+1.8 +0.2	−2.7 +3.8	+4.0 0	+2.7 +0.2	−3.4 +0.7	+2.5 0	+3.4 +1.8	−4.3 +0.7	+2.5 0	+4.3 +1.8

Nominal Size Range, Inches	Class LN 1			Class LN 2			Class LN 3		
	Limits of Interference	Standard Limits		Limits of Interference	Standard Limits		Limits of Interference	Standard Limits	
		Hole H6	Shaft n5		Hole H7	Shaft p6		Hole H7	Shaft r6
Over To	Values shown below are given in thousandths of an inch								
0– 0.12	0 0.45	+0.25 0	+0.45 +0.25	0 0.65	+0.4 0	+0.65 +0.4	0.1 0.75	+0.4 0	+0.75 +0.5
0.12– 0.24	0 0.5	+0.3 0	+0.5 +0.3	0 0.8	+0.5 0	+0.8 +0.5	0.1 0.9	+0.5 0	+0.9 +0.6
0.24– 0.40	0 0.65	+0.4 0	+0.65 +0.4	0 1.0	+0.6 0	+1.0 +0.6	0.2 1.2	+0.6 0	+1.2 +0.8
0.40– 0.71	0 0.8	+0.4 0	+0.8 +0.4	0 1.1	+0.7 0	+1.1 +0.7	0.3 1.4	+0.7 0	+1.4 +1.0
0.71– 1.19	0 1.0	+0.5 0	+1.0 +0.5	0 1.3	+0.8 0	+1.3 +0.8	0.4 1.7	+0.8 0	+1.7 +1.2
1.19– 1.97	0 1.1	+0.6 0	+1.1 +0.6	0 1.6	+1.0 0	+1.6 +1.0	0.4 2.0	+1.0 0	+2.0 +1.4
1.97– 3.15	0.1 1.3	+0.7 0	+1.3 +0.8	0.2 2.1	+1.2 0	+2.1 +1.4	0.4 2.3	+1.2 0	+2.3 +1.6
3.15– 4.73	0.1 1.6	+0.9 0	+1.6 +1.0	0.2 2.5	+1.4 0	+2.5 +1.6	0.6 2.9	+1.4 0	+2.9 +2.0
4.73– 7.09	0.2 1.9	+1.0 0	+1.9 +1.2	0.2 2.8	+1.6 0	+2.8 +1.8	0.9 3.5	+1.6 0	+3.5 +2.5
7.09– 9.85	0.2 2.2	+1.2 0	+2.2 +1.4	0.2 3.2	+1.8 0	+3.2 +2.0	1.2 4.2	+1.8 0	+4.2 +3.0
9.85– 12.41	0.2 2.3	+1.2 0	+2.3 +1.4	0.2 3.4	+2.0 0	+3.4 +2.2	1.5 4.7	+2.0 0	+4.7 +3.5
12.41– 15.75	0.2 2.6	+1.4 0	+2.6 +1.6	0.3 3.9	+2.2 0	+3.9 +2.5	2.3 5.9	+2.2 0	+5.9 +4.5
15.75– 19.69	0.2 2.8	+1.6 0	+2.8 +1.8	0.3 4.4	+2.5 0	+4.4 +2.8	2.5 6.6	+2.5 0	+6.6 +5.0

Table 9. ANSI Standard Force and Shrink Fits *ANSI B4.1-1967 (R1987)*

Nominal Size Range, Inches Over–To	Class FN 1			Class FN 2			Class FN 3			Class FN 4			Class FN 5		
	Interference[a]	Standard Tolerance Limits		Interference[a]	Standard Tolerance Limits		Interference[a]	Standard Tolerance Limits		Interference[a]	Standard Tolerance Limits		Interference[a]	Standard Tolerance Limits	
		Hole H6	Shaft		Hole H7	Shaft s6		Hole H7	Shaft t6		Hole H7	Shaft u6		Hole H8	Shaft x7
	Values shown below are in thousandths of an inch														
0–0.12	0.05	+0.25	+0.5	0.2	+0.4	+0.85				0.3	+0.4	+0.95	0.3	+0.6	+1.3
	0.5	0	+0.3	0.85	0	+0.6				0.95	0	+0.7	1.3	0	+0.9
0.12–0.24	0.1	+0.3	+0.6	0.2	+0.5	+1.0				0.4	+0.5	+1.2	0.5	+0.7	+1.7
	0.6	0	+0.4	1.0	0	+0.7				1.2	0	+0.9	1.7	0	+1.2
0.24–0.40	0.1	+0.4	+0.75	0.4	+0.6	+1.4				0.6	+0.6	+1.6	0.5	+0.9	+2.0
	0.75	0	+0.5	1.4	0	+1.0				1.6	0	+1.2	2.0	0	+1.4
0.40–0.56	0.1	+0.4	+0.8	0.5	+0.7	+1.6				0.7	+0.7	+1.8	0.6	+1.0	+2.3
	0.8	0	+0.5	1.6	0	+1.2				1.8	0	+1.4	2.3	0	+1.6
0.56–0.71	0.2	+0.4	+0.9	0.5	+0.7	+1.6				0.7	+0.7	+1.8	0.8	+1.0	+2.5
	0.9	0	+0.6	1.6	0	+1.2				1.8	0	+1.4	2.5	0	+1.8
0.71–0.95	0.2	+0.5	+1.1	0.6	+0.8	+1.9				0.8	+0.8	+2.1	1.0	+1.2	+3.0
	1.1	0	+0.7	1.9	0	+1.4				2.1	0	+1.6	3.0	0	+2.2
0.95–1.19	0.3	+0.5	+1.2	0.6	+0.8	+1.9	0.8	+0.8	+2.1	+1.0	+0.8	+2.3	1.3	+1.2	+3.3
	1.2	0	+0.8	1.9	0	+1.4	2.1	0	+1.6	2.3	0	+1.8	3.3	0	+2.5
1.19–1.58	0.3	+0.6	+1.3	0.8	+1.0	+2.4	1.0	+1.0	+2.6	1.5	+1.0	+3.1	1.4	+1.6	+4.0
	1.3	0	+0.9	2.4	0	+1.8	2.6	0	+2.0	3.1	0	+2.5	4.0	0	+3.0
1.58–1.97	0.4	+0.6	+1.4	0.8	+1.0	+2.4	1.2	+1.0	+2.8	1.8	+1.0	+3.4	2.4	+1.6	+5.0
	1.4	0	+1.0	2.4	0	+1.8	2.8	0	+2.2	3.4	0	+2.8	5.0	0	+4.0
1.97–2.56	0.6	+0.7	+1.8	0.8	+1.2	+2.7	1.3	+1.2	+3.2	2.3	+1.2	+4.2	3.2	+1.8	+6.2
	1.8	0	+1.3	2.7	0	+2.0	3.2	0	+2.5	4.2	0	+3.5	6.2	0	+5.0
2.56–3.15	0.7	+0.7	+1.9	1.0	+1.2	+2.9	1.8	+1.2	+3.7	2.8	+1.2	+4.7	4.2	+1.8	+7.2
	1.9	0	+1.4	2.9	0	+2.2	3.7	0	+3.0	4.7	0	+4.0	7.2	0	+6.0
3.15–3.94	0.9	+0.9	+2.4	1.4	+1.4	+3.7	2.1	+1.4	+4.4	3.6	+1.4	+5.9	4.8	+2.2	+8.4
	2.4	0	+1.8	3.7	0	+2.8	4.4	0	+3.5	5.9	0	+5.0	8.4	0	+7.0
3.94–4.73	1.1	+0.9	+2.6	1.6	+1.4	+3.9	2.6	+1.4	+4.9	4.6	+1.4	+6.9	5.8	+2.2	+9.4
	2.6	0	+2.0	3.9	0	+3.0	4.9	0	+4.0	6.9	0	+6.0	9.4	0	+8.0

Table 9. *(Continued)* **ANSI Standard Force and Shrink Fits** *ANSI B4.1-1967 (R1987)*

Nominal Size Range, Inches Over–To	Class FN 1			Class FN 2			Class FN 3			Class FN 4			Class FN 5		
	Interference[a]	Standard Tolerance Limits		Interference[a]	Standard Tolerance Limits		Interference[a]	Standard Tolerance Limits		Interference[a]	Standard Tolerance Limits		Interference[a]	Standard Tolerance Limits	
		Hole H6	Shaft		Hole H7	Shaft s6		Hole H7	Shaft t6		Hole H7	Shaft u6		Hole H8	Shaft x7
	Values shown below are in thousandths of an inch														
4.73–5.52	1.2	+1.0	+2.9	1.9	+1.6	+4.5	3.4	+1.6	+6.0	5.4	+1.6	+8.0	7.5	+2.5	+11.6
	2.9	0	+2.2	4.5	0	+3.5	6.0	0	+5.0	8.0	0	+7.0	11.6	0	+10.0
5.52–6.30	1.5	+1.0	+3.2	2.4	+1.6	+5.0	3.4	+1.6	+6.0	5.4	+1.6	+8.0	9.5	+2.5	+13.6
	3.2	0	+2.5	5.0	0	+4.0	6.0	0	+5.0	8.0	0	+7.0	13.6	0	+12.0
6.30–7.09	1.8	+1.0	+3.5	2.9	+1.6	+5.5	4.4	+1.6	+7.0	6.4	+1.6	+9.0	9.5	+2.5	+13.6
	3.5	0	+2.8	5.5	0	+4.5	7.0	0	+6.0	9.0	0	+8.0	13.6	0	+12.0
7.09–7.88	1.8	+1.2	+3.8	3.2	+1.8	+6.2	5.2	+1.8	+8.2	7.2	+1.8	+10.2	11.2	+2.8	+15.8
	3.8	0	+3.0	6.2	0	+5.0	8.2	0	+7.0	10.2	0	+9.0	15.8	0	+14.0
7.88–8.86	2.3	+1.2	+4.3	3.2	+1.8	+6.2	5.2	+1.8	+8.2	8.2	+1.8	+11.2	13.2	+2.8	+17.8
	4.3	0	+3.5	6.2	0	+5.0	8.2	0	+7.0	11.2	0	+10.0	17.8	0	+16.0
8.86–9.85	2.3	+1.2	+4.3	4.2	+1.8	+7.2	6.2	+1.8	+9.2	10.2	+1.8	+13.2	13.2	+2.8	+17.8
	4.3	0	+3.5	7.2	0	+6.0	9.2	0	+8.0	13.2	0	+12.0	17.8	0	+16.0
9.85–11.03	2.8	+1.2	+4.9	4.0	+2.0	+7.2	7.0	+2.0	+10.2	10.0	+2.0	+13.2	15.0	+3.0	+20.0
	4.9	0	+4.0	7.2	0	+6.0	10.2	0	+9.0	13.2	0	+12.0	20.0	0	+18.0
11.03–12.41	2.8	+1.2	+4.9	5.0	+2.0	+8.2	7.0	+2.0	+10.2	12.0	+2.0	+15.2	17.0	+3.0	+22.0
	4.9	0	+4.0	8.2	0	+7.0	10.2	0	+9.0	15.2	0	+14.0	22.0	0	+20.0
12.41–13.98	3.1	+1.4	+5.5	5.8	+2.2	+9.4	7.8	+2.2	+11.4	13.8	+2.2	+17.4	18.5	+3.5	+24.2
	5.5	0	+4.5	9.4	0	+8.0	11.4	0	+10.0	17.4	0	+16.0	24.2	0	+22.0
13.98–15.75	3.6	+1.4	+6.1	5.8	+2.2	+9.4	9.8	+2.2	+13.4	15.8	+2.2	+19.4	21.5	+3.5	+27.2
	6.1	0	+5.0	9.4	0	+8.0	13.4	0	+12.0	19.4	0	+18.0	27.2	0	+25.0
15.75–17.72	4.4	+1.6	+7.0	6.5	+2.5	+10.6	+9.5	+2.5	+13.6	17.5	+2.5	+21.6	24.0	+4.0	+30.5
	7.0	0	+6.0	10.6	0	+9.0	13.6	0	+12.0	21.6	0	+20.0	30.5	0	+28.0
17.72–19.69	4.4	+1.6	+7.0	7.5	+2.5	+11.6	11.5	+2.5	+15.6	19.5	+2.5	+23.6	26.0	+4.0	+32.5
	7.0	0	+6.0	11.6	0	+10.0	15.6	0	+14.0	23.6	0	+22.0	32.5	0	+30.0

ALLOWANCES AND TOLERANCES

Appendix B

Economy of Manufacturing

Table 6: U.S. Manufacturing Employment for December 2007

U.S. total and manufacturing employment, December 2007

	Employment (thousands)				
	Total	*Manufacturing*	*Manufacturing share of total employment*	*Jobs lost since March 1998 (in thousands)*	*Manufacturing jobs lost as a share of total employment in 1998*
UNITED STATES	138,495	13,919	10.1%	- 3,718	-3.0%
NORTHEAST	25,717	2,215	8.6	- 868	-3.6
New England	7,061	703	10.0	- 271	-4.0
Connecticut	1,703	191	11.2	- 59	-3.6
Maine	620	58	9.3	- 23	-4.2
Massachusetts	3,282	294	9.0	- 124	-3.9
New Hampshire	648	75	11.5	- 30	-5.1
Rhode Island	499	50	10.1	- 26	-5.7
Vermont	309	36	11.5	- 9	-3.2
Middle Atlantic	18,656	1,512	8.1	- 597	-3.4
New Jersey	4,115	316	7.7	- 116	-3.1
New York	8,723	541	6.2	- 258	-3.2
Pennsylvania	5,818	655	11.3	- 223	-4.1
MIDWEST	31,761	4,322	13.6	- 1,170	-3.8
East North Central	21,546	3,104	14.4	- 982	-4.6
Illinois	5,991	673	11.2	- 237	-4.1
Indiana	2,986	554	18.5	- 107	-3.7
Michigan	4,248	606	14.3	- 288	-6.4
Ohio	5,428	774	14.3	- 256	-4.7
Wisconsin	2,893	496	17.2	- 94	-3.5
West North Central	10,215	1,218	11.9	- 188	-2.0
Iowa	1,528	231	15.1	- 16	-1.1
Kansas	1,384	187	13.5	- 17	-1.3
Minnesota	2,768	336	12.2	- 62	-2.4
Missouri	2,797	294	10.5	- 83	-3.1
Nebraska	969	101	10.5	- 12	-1.4
North Dakota	361	26	7.2	3	1.0
South Dakota	409	43	10.5	- 1	-0.3
SOUTH	49,732	4,643	9.3	- 1,284	-2.9
South Atlantic	26,752	2,114	7.9	- 733	-3.2
*Delaware**	441	32	7.2	- 13	-3.2
*District of Columbia**	704	2	0.2	3	-0.4
Florida	8,155	390	4.8	- 81	-1.2
Georgia	4,171	432	10.4	- 120	-3.2
Maryland	2,636	134	5.1	- 43	-1.9
North Carolina	4,133	540	13.1	- 262	-7.0
South Carolina	1,939	240	12.4	- 102	-5.8
Virginia	3,810	286	7.5	- 90	-2.8
West Virginia	763	59	7.7	- 19	-2.7

* Non-seasonally adjusted data are used for Alaska, D. C., Delaware, Hawaii, Oklahoma, and Wyoming.

cont. on page 3

Table 7: Continued U.S. Manufacturing Employment

U.S. total and manufacturing employment, December 2007

	Employment (thousands)				
	Total	*Manufacturing*	*Manufacturing share of total employment*	*Jobs lost since March 1998 (in thousands)*	*Manufacturing jobs lost as a share of total employment in 1998*
UNITED STATES	138,495	13,919	10.1%	- 3,718	-3.0%
East South Central	7,867	1,110	14.1	- 298	-4.0
Alabama	2,022	298	14.7	- 66	-3.5
Kentucky	1,857	253	13.6	- 52	-3.0
Mississippi	1,171	172	14.7	- 60	-5.4
Tennessee	2,817	387	13.7	- 120	-4.6
West South Central	15,113	1,420	9.4	- 254	-1.9
Arkansas	1,208	187	15.5	- 55	-4.9
Louisiana	1,929	154	8.0	- 32	-1.7
*Oklahoma**	1,586	151	9.5	- 23	-1.6
Texas	10,390	927	8.9	- 145	-1.6
WEST	30,822	2,662	8.6	- 541	-2.1
Mountain	9,893	642	6.5	- 73	-0.9
Arizona	2,720	187	6.9	- 26	-1.2
Colorado	2,346	143	6.1	- 48	-2.4
Idaho	659	64	9.6	- 6	-1.2
Montana	450	21	4.6	- 1	-0.3
Nevada	1,308	52	4.0	12	1.3
New Mexico	848	36	4.3	- 7	-0.9
Utah	1,272	129	10.2	2	0.2
*Wyoming**	291	11	3.6	1	0.3
Pacific	20,929	2,020	9.7	- 468	-2.5
*Alaska**	317	13	4.0	- 1	-0.3
California	15,291	1,493	9.8	- 372	-2.8
*Hawaii**	632	15	2.4	- 1	-0.2
Oregon	1,739	204	11.8	- 27	-1.7
Washington	2,949	296	10.0	- 68	-2.6

* Non-seasonally adjusted data are used for Alaska, D. C., Delaware, Hawaii, Oklahoma, and Wyoming.
SOURCE: Bureau of Labor Statistics and EPI analysis.

(U.S. Department of Labor, Bureau of Labor Statistics, 2008)

Table 8: Manufacturing Pay Scale Against the Rest of the Economy

For workers without a college degree, manufacturing jobs pay more than jobs in the rest of the economy (average hourly wages)*

State	Average hourly wage: Manufacturing	Average hourly wage: Non-manufacturing	Manufacturing wage premium: Dollars per hour	Manufacturing wage premium: Percent
U.S. average	$16.49	$15.10	$1.38	9.2%
Alabama	$15.30	$14.27	$1.03	7.2%
Alaska	21.30	18.35	2.95	16.1
Arizona	17.07	14.96	2.11	14.1
Arkansas	13.93	13.40	0.52	3.9
California	16.56	16.26	0.30	1.8
Colorado	17.83	16.27	1.56	9.6
Connecticut	19.12	16.66	2.46	14.8
Delaware	19.25	16.21	3.04	18.7
District of Columbia	15.25	15.05	0.20	1.3
Florida	16.58	15.11	1.47	9.8
Georgia	15.39	14.60	0.79	5.4
Hawaii	15.85	15.81	0.04	0.2
Idaho	15.89	14.46	1.43	9.9
Illinois	16.65	15.25	1.40	9.2
Indiana	16.77	14.80	1.98	13.3
Iowa	15.51	14.24	1.27	8.9
Kansas	17.22	14.05	3.17	22.5
Kentucky	15.71	13.90	1.81	13.0
Louisiana	16.48	14.37	2.12	14.7
Maine	16.92	14.04	2.88	20.5
Maryland	17.71	17.31	0.40	2.3
Massachusetts	17.30	15.87	1.43	9.0
Michigan	18.17	14.71	3.46	23.5
Minnesota	17.19	15.70	1.49	9.5
Mississippi	14.31	13.21	1.10	8.4
Missouri	16.15	14.84	1.31	8.8
Montana	15.10	13.65	1.45	10.7
Nebraska	14.14	13.84	0.30	2.1
Nevada	16.27	16.18	0.09	0.6
New Hampshire	18.64	16.46	2.18	13.3
New Jersey	17.94	17.08	0.85	5.0
New Mexico	17.11	14.17	2.94	20.8
New York	16.03	15.83	0.20	1.2
North Carolina	15.03	13.97	1.06	7.6
North Dakota	14.18	13.51	0.67	5.0

Table 9: Continues Manufacturing Pay Scale Against Rest of the Economy

For workers without a college degree, manufacturing jobs pay more than jobs in the rest of the economy (average hourly wages)*

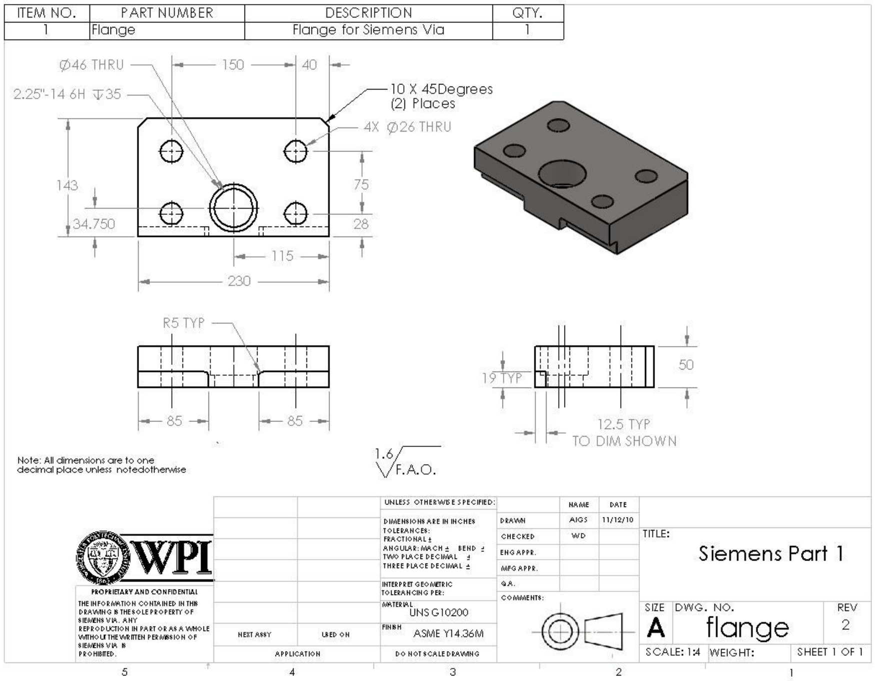
State	Average hourly wage: Manufacturing	Average hourly wage: Non-manufacturing	Manufacturing wage premium: Dollars per hour	Manufacturing wage premium: Percent
Ohio	$16.74	$14.51	$2.23	15.4%
Oklahoma	16.60	13.77	2.83	20.6
Oregon	17.16	14.85	2.31	15.6
Pennsylvania	16.70	14.91	1.78	12.0
Rhode Island	15.55	15.49	0.07	0.4
South Carolina	16.45	13.59	2.86	21.1
South Dakota	13.75	13.61	0.14	1.0
Tennessee	14.14	13.57	0.58	4.2
Texas	16.08	13.81	2.27	16.4
Utah	15.03	14.61	0.42	2.9
Vermont	16.60	15.13	1.47	9.7
Virginia	17.08	15.56	1.52	9.8
Washington	19.88	16.52	3.36	20.3
West Virginia	16.25	14.68	1.57	10.7
Wisconsin	16.75	14.87	1.89	12.7
Wyoming	17.91	15.73	2.18	13.8

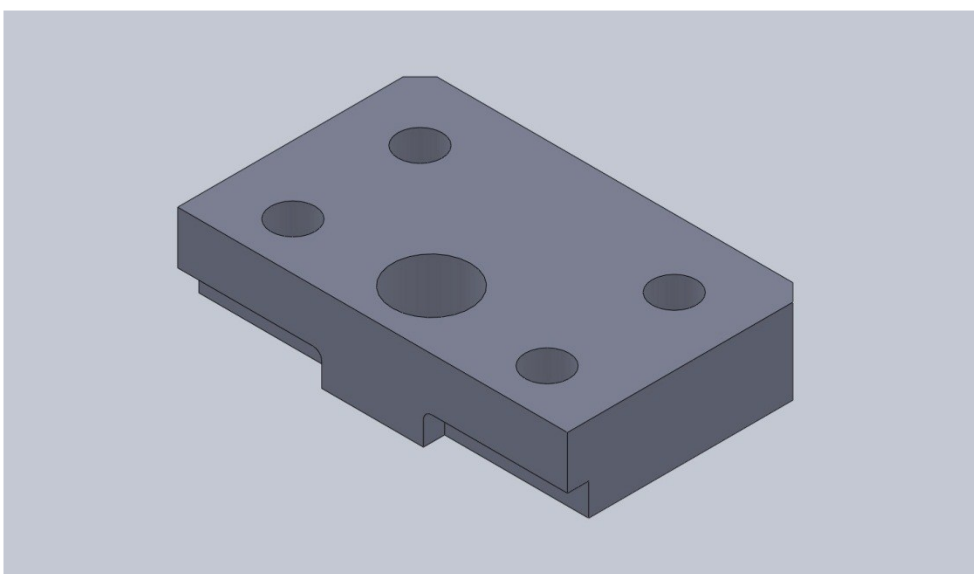
* Hourly wage of workers with less than a college degree of manufacturing verus non-manufacturing industries in 2006-07 by state; data in 2007 dollars.

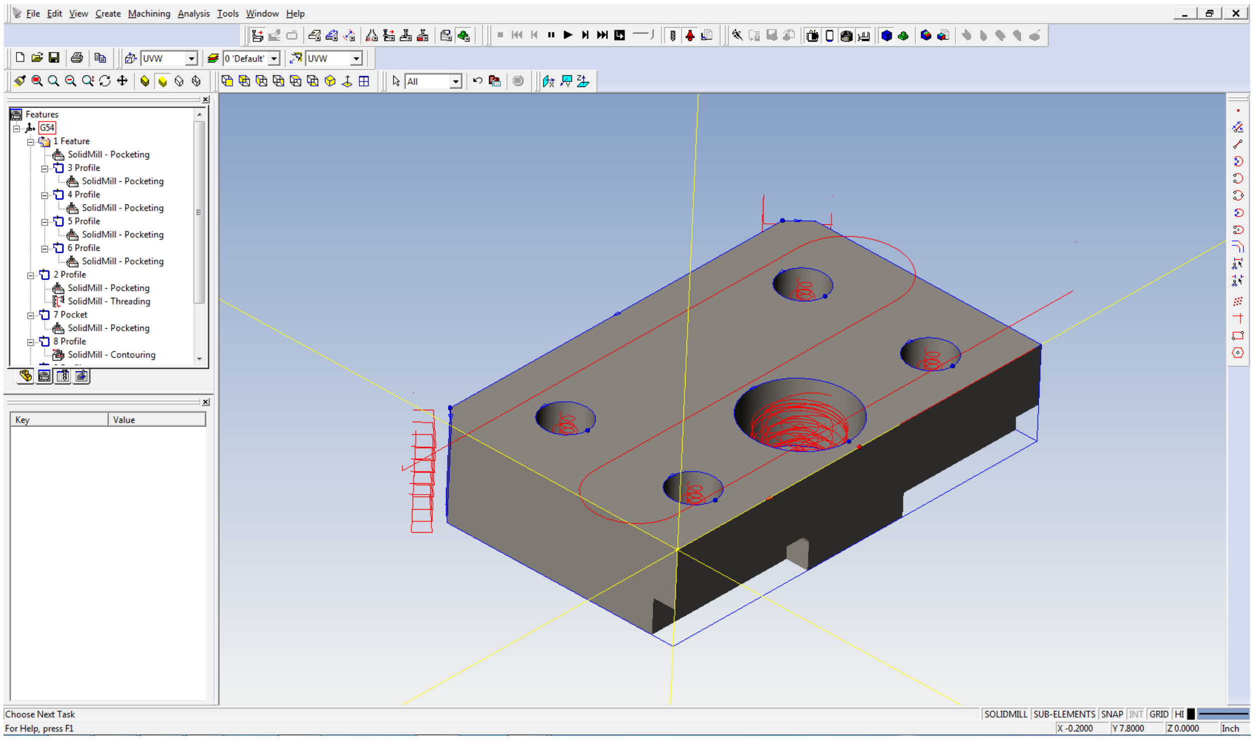
(U.S. Department of Labor, Bureau of Labor Statistics, 2007)

Appendix C: Engineering Graphics

Flange



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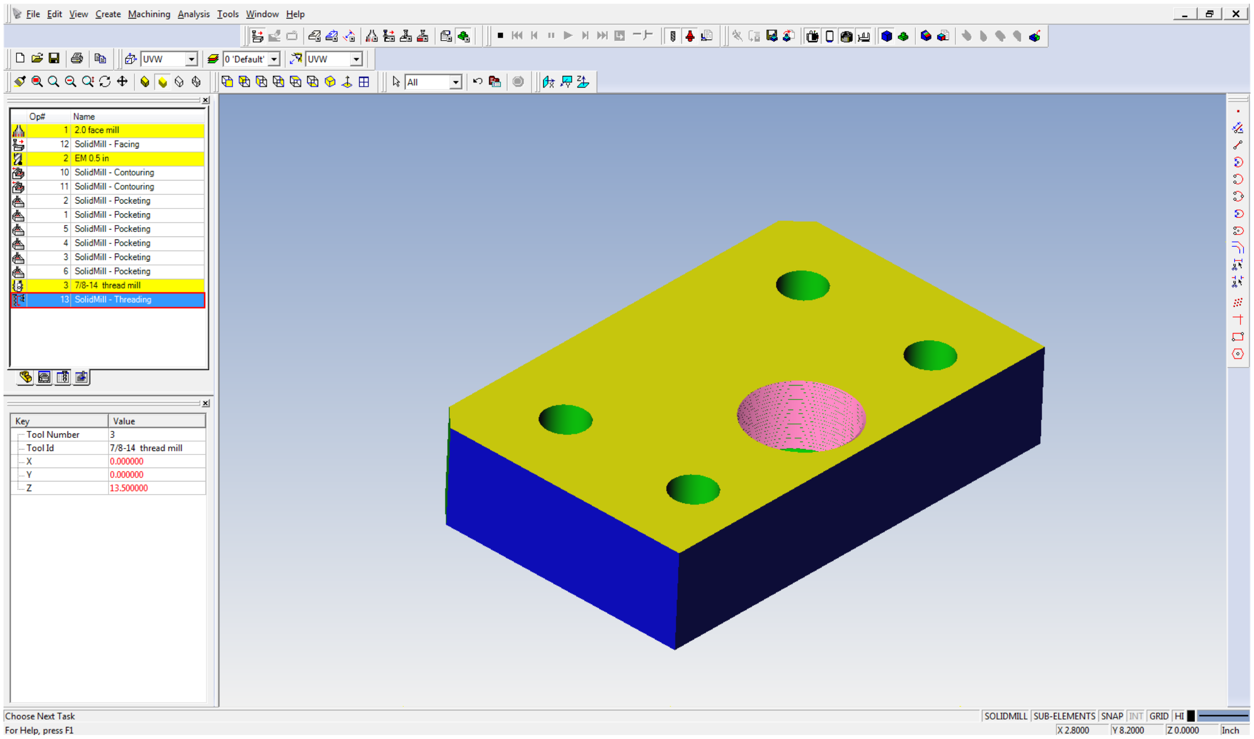
Features
G54
1 Feature
SolidMill - Pocketing
3 Profile
SolidMill - Pocketing
4 Profile
SolidMill - Pocketing
5 Profile
SolidMill - Pocketing
6 Profile
SolidMill - Pocketing
2 Profile
SolidMill - Pocketing
SolidMill - Threading
7 Pocket
SolidMill - Pocketing
8 Profile
SolidMill - Contouring
Key
Value
Choose Next Task
For Help, press F1
SOLIDMILL
SUB-ELEMENTS
SNAP
GRID
X -0.2000
Y 7.8000
Z 0.0000
Inch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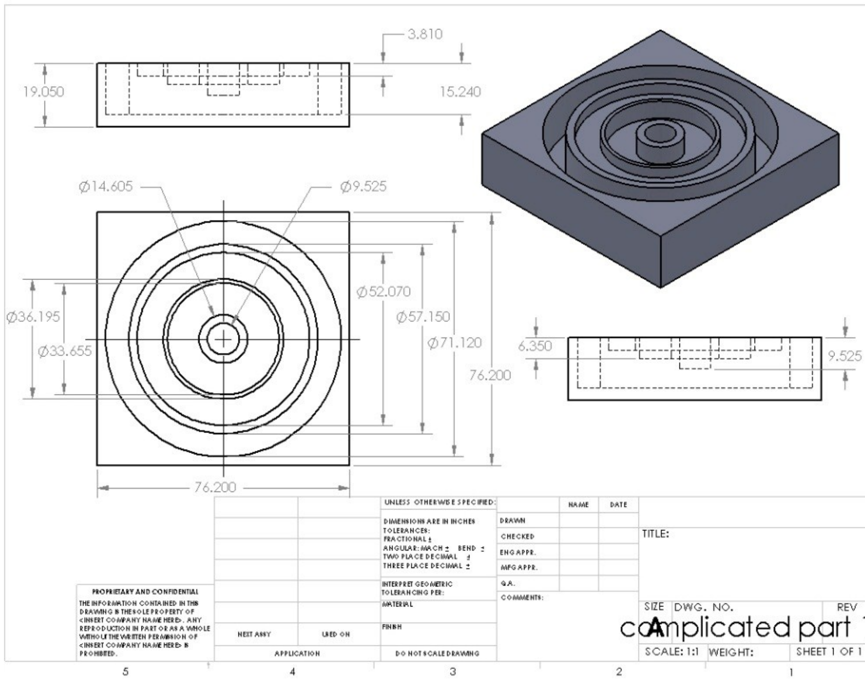
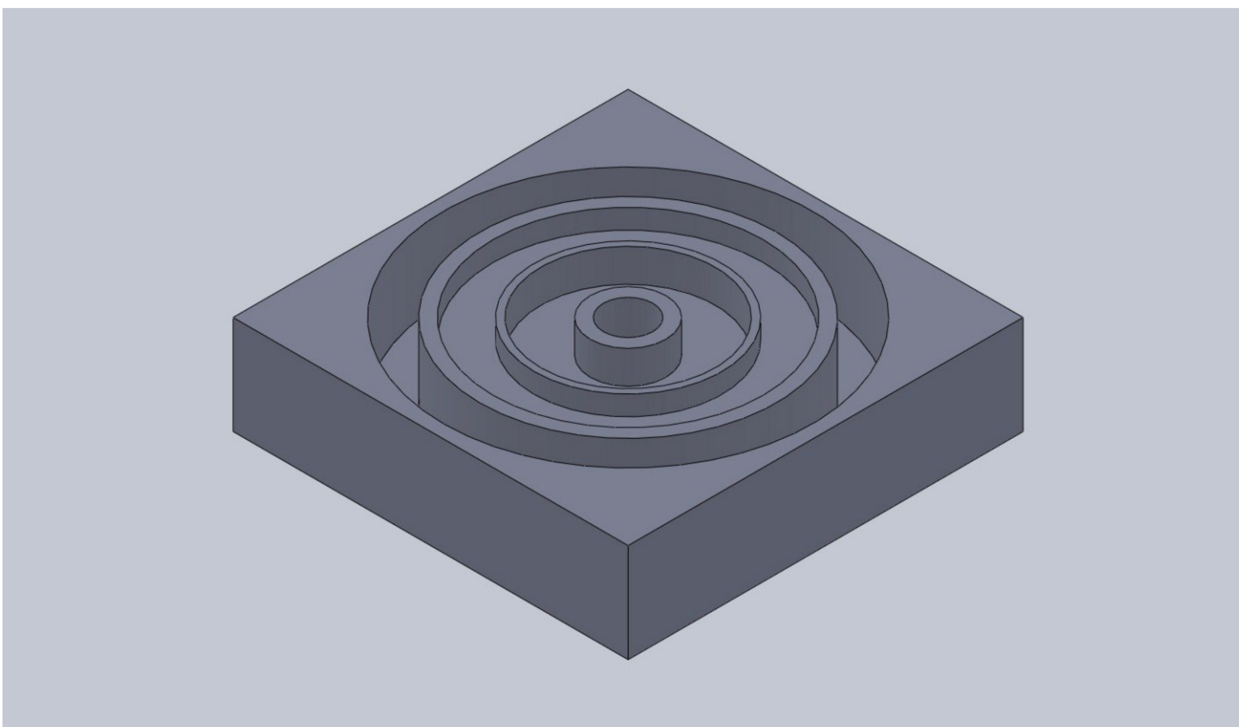
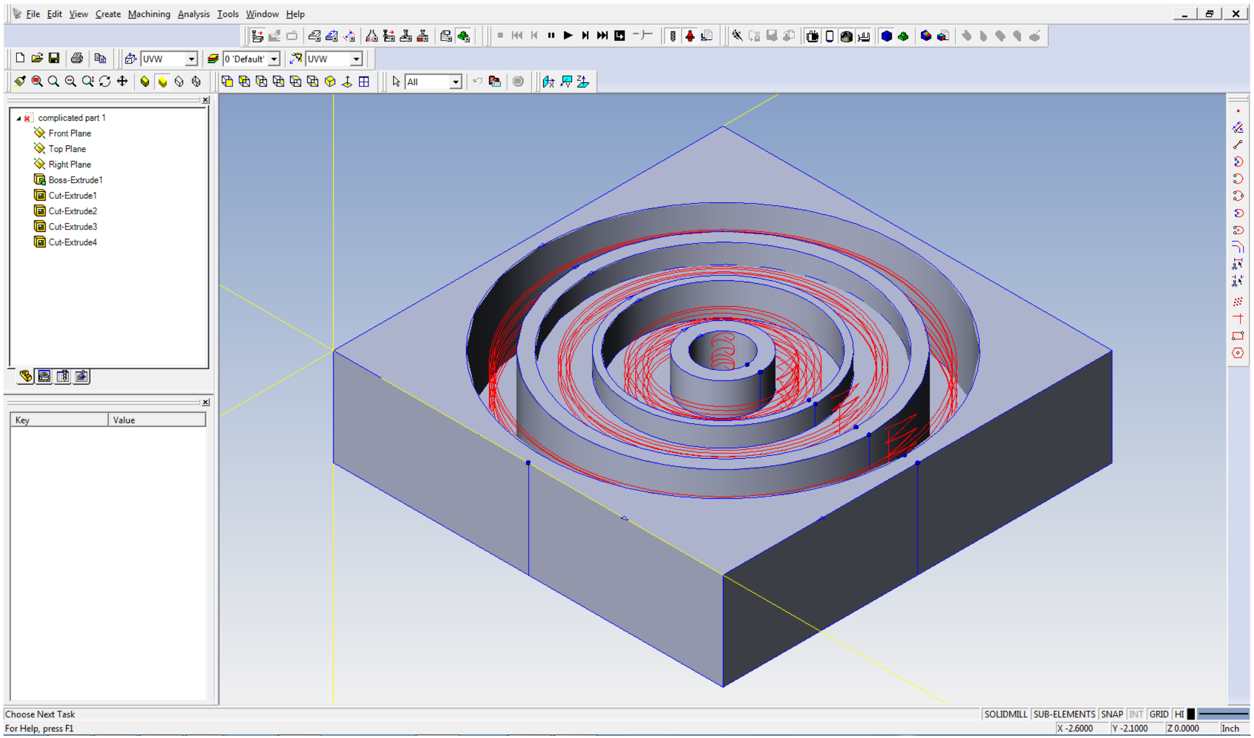
Op# Name
1 2.0 face mill
12 SolidMill - Facing
2 EM 0.5 in
10 SolidMill - Contouring
11 SolidMill - Contouring
2 SolidMill - Pocketing
1 SolidMill - Pocketing
5 SolidMill - Pocketing
4 SolidMill - Pocketing
3 SolidMill - Pocketing
6 SolidMill - Pocketing
3 7/8-14 thread mill
13 SolidMill - Threading
Key Value
Tool Number 3
Tool Id 7/8-14 thread mill
X 0.000000
Y 0.000000
Z 13.500000
Choose Next Task
For Help, press F1
SOLIDMILL
SUB-ELEMENTS
SNAP
GRID
X 2.8000
Y 8.2000
Z 0.0000
Inch

Practice part 2



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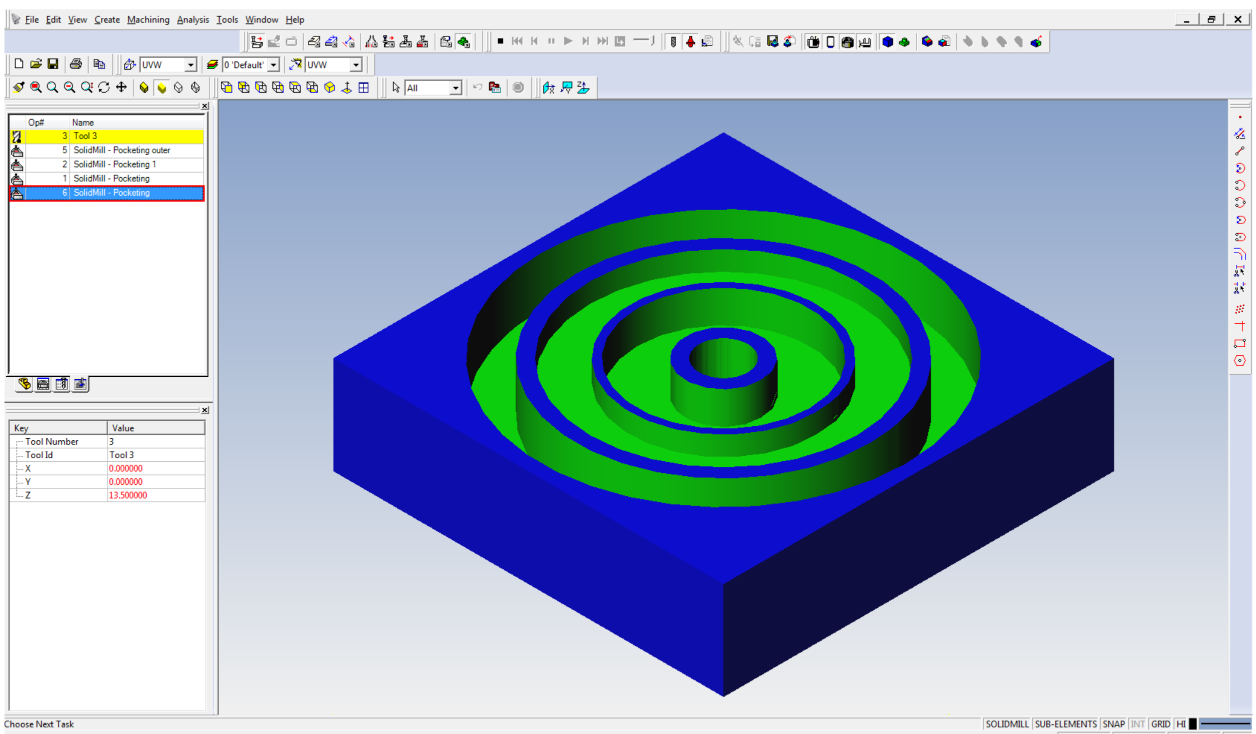
complicated part 1
Front Plane
Top Plane
Right Plane
Boss-Extrude1
Cut-Extrude1
Cut-Extrude2
Cut-Extrude3
Cut-Extrude4
Key
Value
Choose Next Task
For Help, press F1
SOLIDMILL SUB-ELEMENTS SNAP INT GRID HI
X -2.6000 Y -2.1000 Z 0.0000 Inch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Op# Name
3 Tool 3
5 SolidMill - Pocketing outer
2 SolidMill - Pocketing 1
1 SolidMill - Pocketing
6 SolidMill - Pocketing
Key Value
Tool Number 3
Tool Id Tool 3
X 0.000000
Y 0.000000
Z 13.500000
Choose Next Task
For Help, press F1
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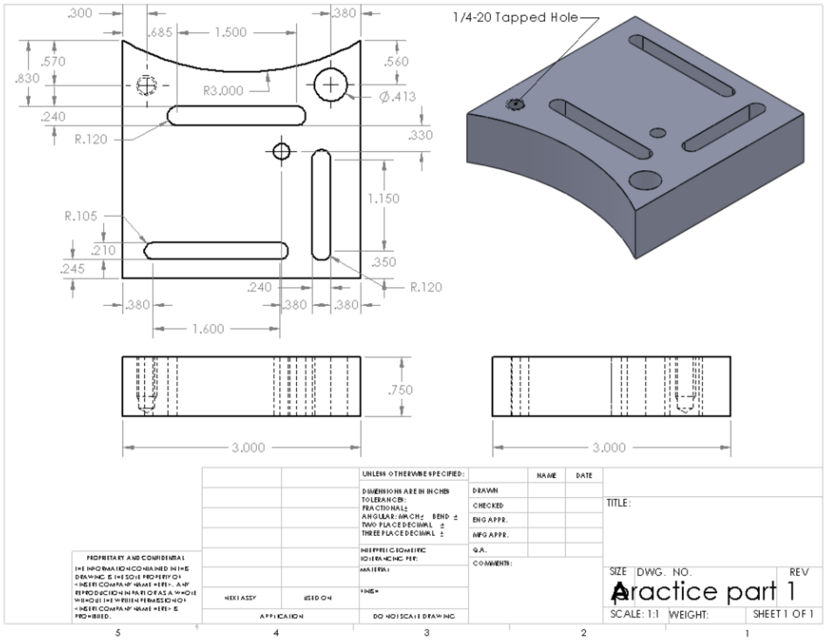
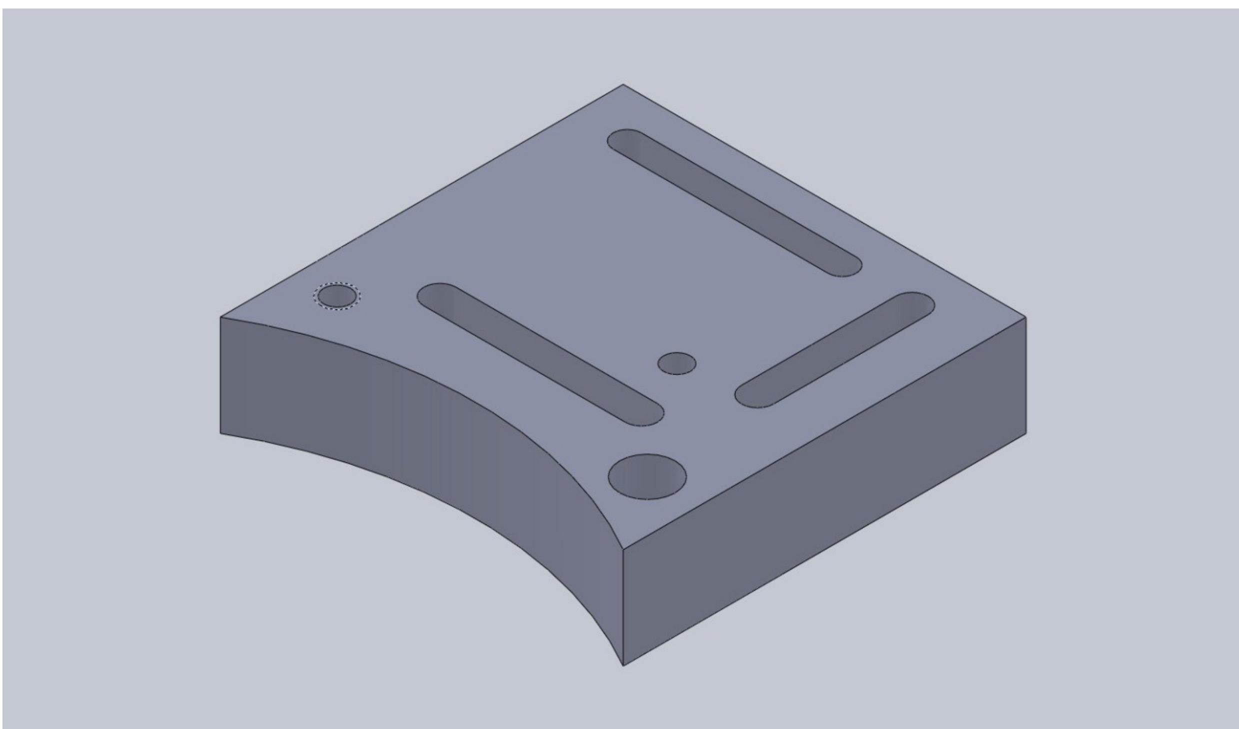
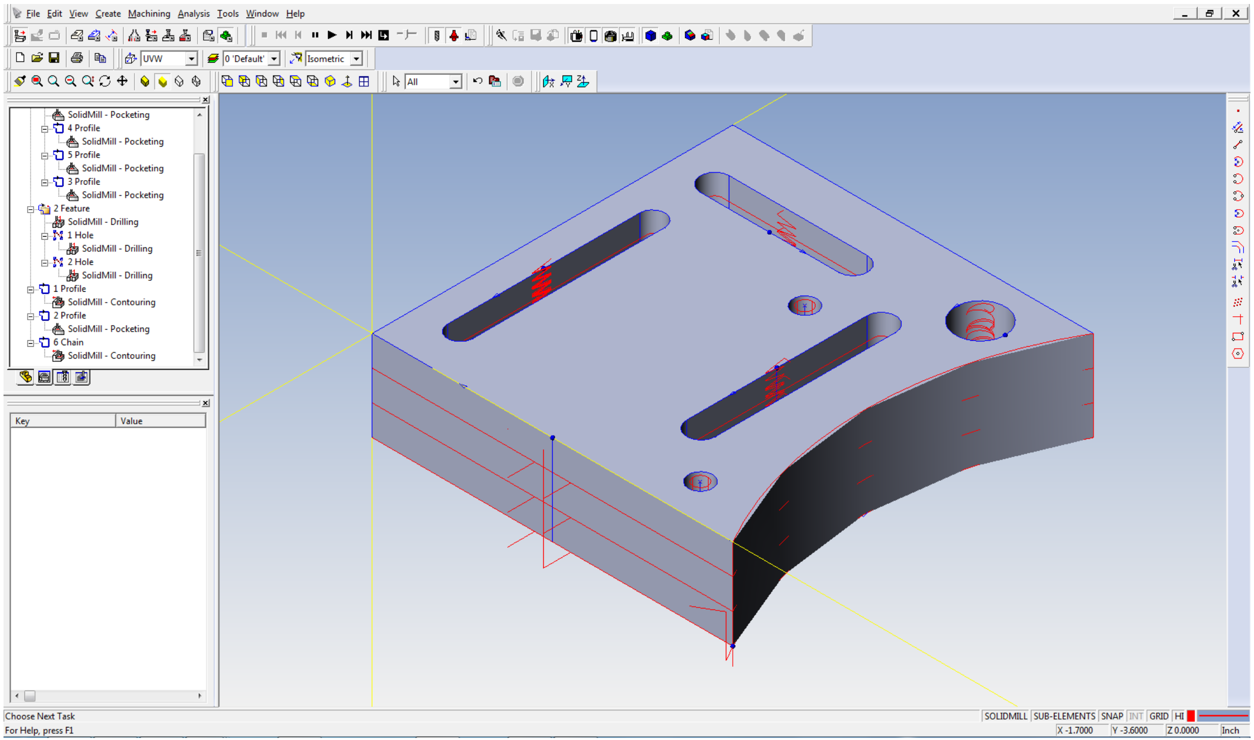
X -1.7000 Y -3.0000 Z 0.0000 Inch

Practice Part 1



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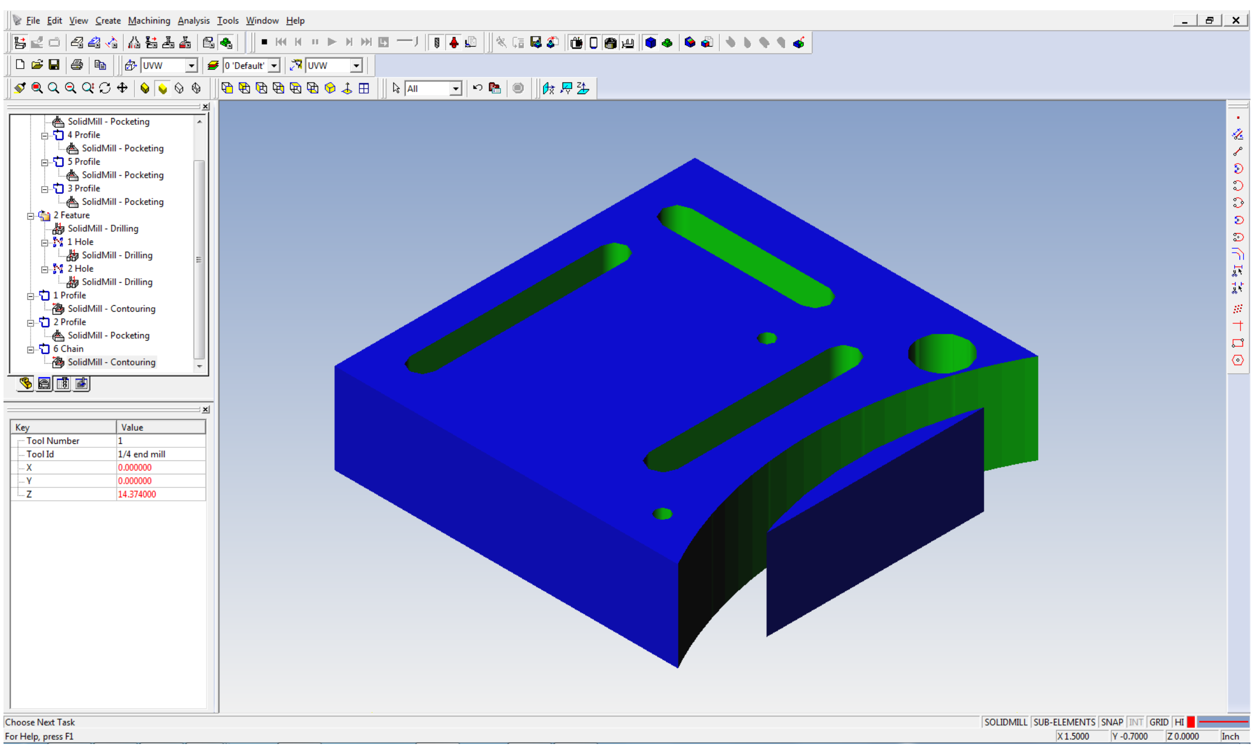
SolidMill - Pocketing
4 Profile
SolidMill - Pocketing
5 Profile
SolidMill - Pocketing
3 Profile
SolidMill - Pocketing
2 Feature
SolidMill - Drilling
1 Hole
SolidMill - Drilling
2 Hole
SolidMill - Drilling
1 Profile
SolidMill - Contouring
2 Profile
SolidMill - Pocketing
6 Chain
SolidMill - Contouring
Key
Value
Choose Next Task
For Help, press F1
SOLIDMILL SUB-ELEMENTS SNAP INT GRID HI
X -1.7000 Y -3.6000 Z 0.0000 Inch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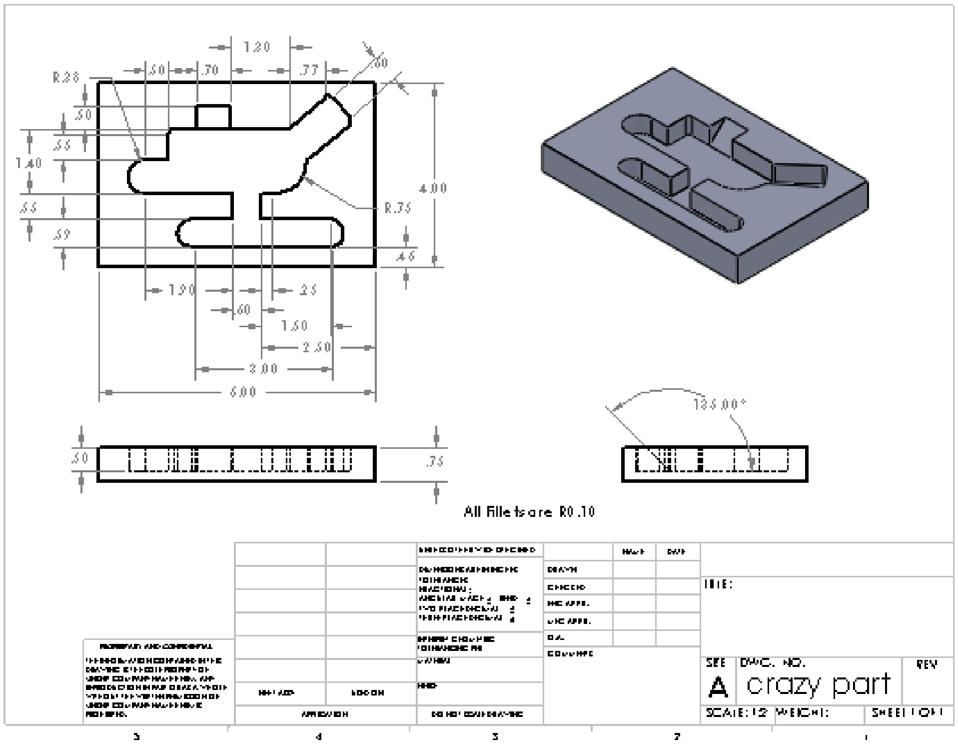
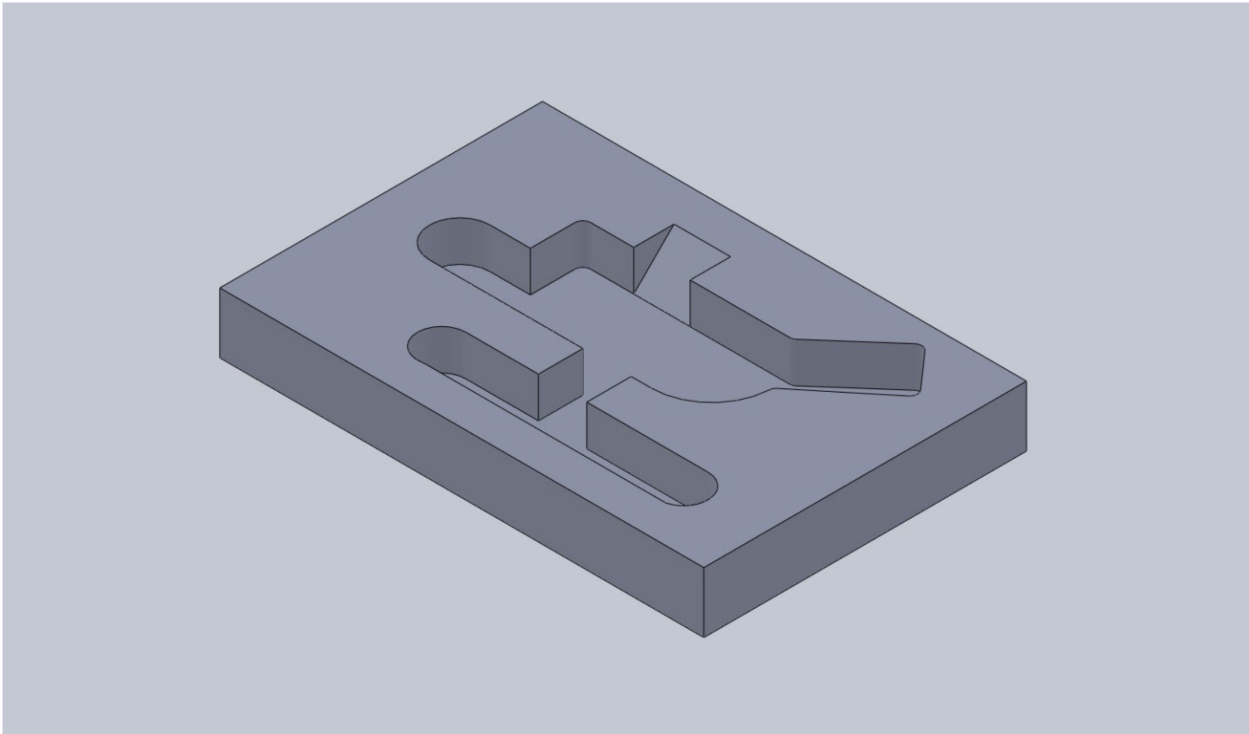
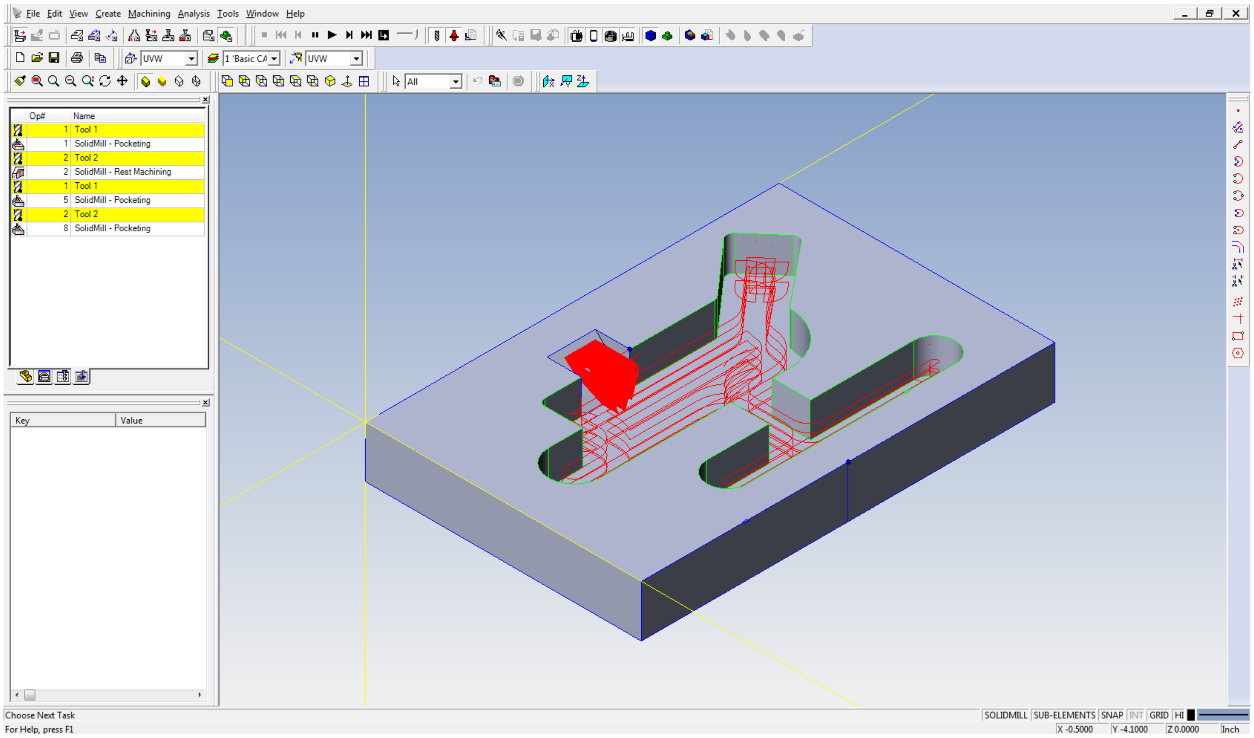
SolidMill - Pocketing
4 Profile
SolidMill - Pocketing
5 Profile
SolidMill - Pocketing
3 Profile
SolidMill - Pocketing
2 Feature
SolidMill - Drilling
1 Hole
SolidMill - Drilling
2 Hole
SolidMill - Drilling
1 Profile
SolidMill - Contouring
2 Profile
SolidMill - Pocketing
6 Chain
SolidMill - Contouring
Key
Value
Tool Number 1
Tool Id 1/4 end mill
X 0.000000
Y 0.000000
Z 14.374000
Choose Next Task
For Help, press F1
SOLIDMILL SUB-ELEMENTS SNAP INT GRID HI
X 1.5000 Y -0.7000 Z 0.0000 Inch

Crazy Part



All Fillets are R0.10
TITLE:
SIZE
DWG. NO.
REV
A
crazy part
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

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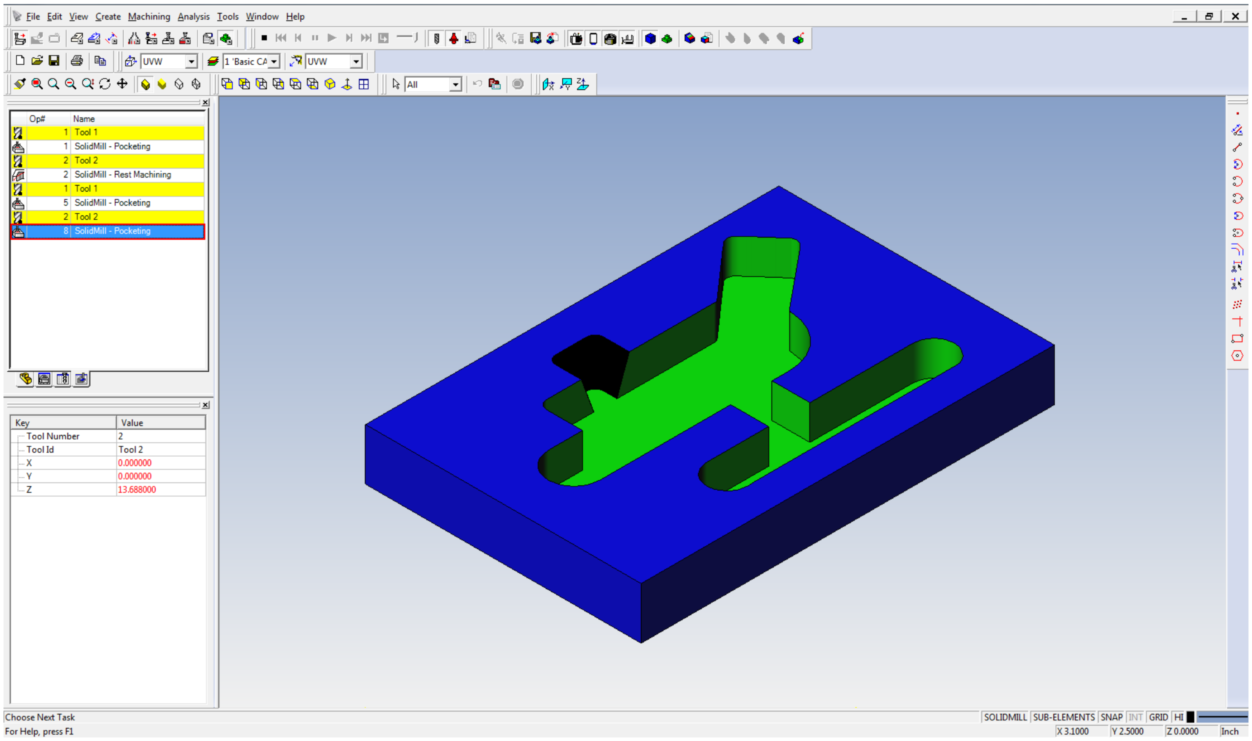
Op# Name
1 Tool 1
1 SolidMill - Pocketing
2 Tool 2
2 SolidMill - Rest Machining
1 Tool 1
5 SolidMill - Pocketing
2 Tool 2
8 SolidMill - Pocketing
Key Value
Choose Next Task
For Help, press F1
SOLIDMILL SUB-ELEMENTS SNAP INT GRID
X -0.5000 Y -4.1000 Z 0.0000 Inch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Op# Name
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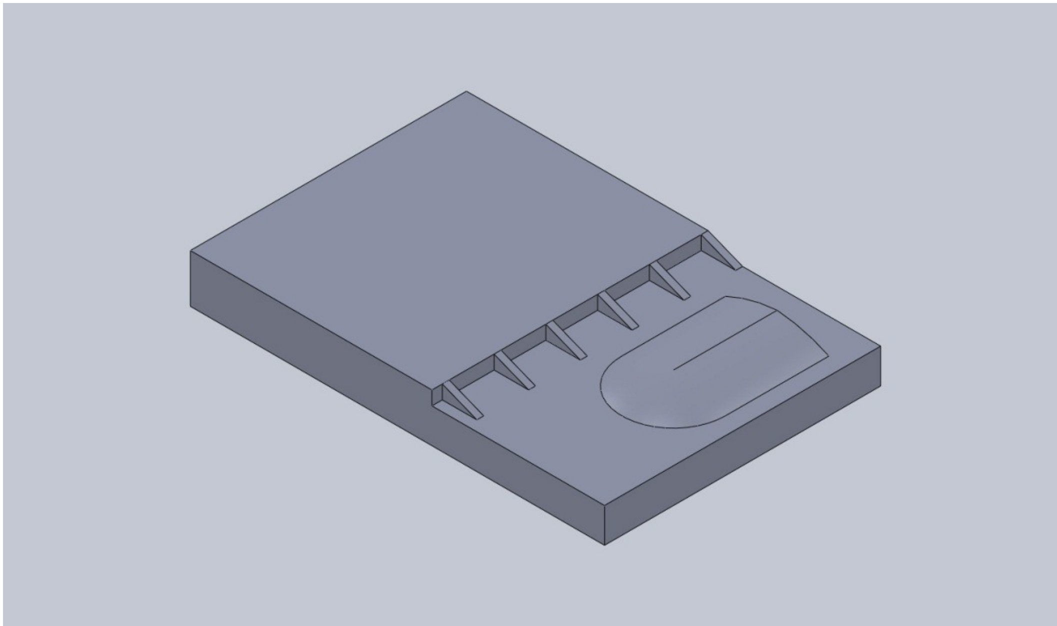
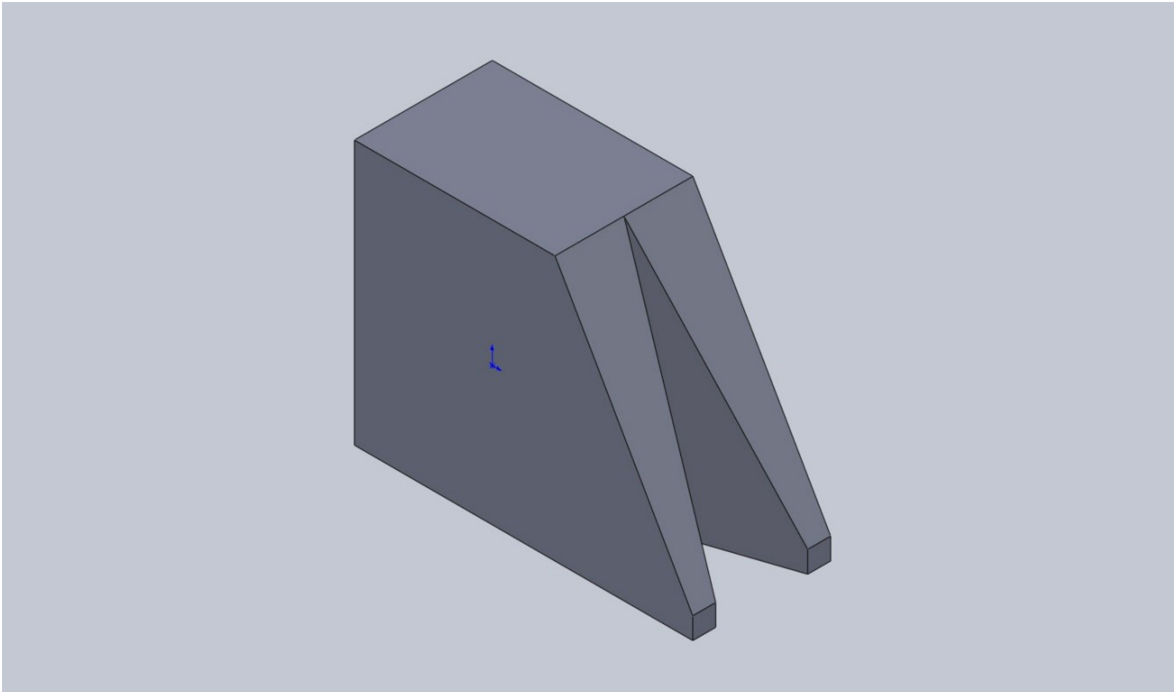
1 SolidMill - Pocketing
2 Tool 2
2 SolidMill - Rest Machining
1 Tool 1
5 SolidMill - Pocketing
2 Tool 2
8 SolidMill - Pocketing
Key Value
Tool Number 2
Tool Id Tool 2
X 0.000000
Y 0.000000
Z 13.688000
Choose Next Task
For Help, press F1
SOLIDMILL SUB-ELEMENTS SNAP INT GRID
X 3.1000 Y 2.5000 Z 0.0000 Inch

Extra Solid Models





Appendix D: CNC Code

Mill G-Code

G00	RAPID POSITIONING MOTION (X,Z,U,W,B) (SETTING 10, 101)
G01	LINEAR INTERPOLATION MOTION (X,Z,U,W,B,F)
G01	LINEAR INTERPOLATION MOTION (X,Z,U,W,B,F)
G02	CW CIRCULAR INTERPOLATION MOTION (X,Z,U,W,I,K,R,F)
G03	CCW CIRCULAR INTERPOLATION MOTION (X,Z,U,W,I,K,R,F)
G04	DWELL (P) (P=time, seconds)
G05	FINE SPINDLE CONTROL MOTION (X,Z,U,W,R,F) (LIVE TOOLING)
G09	EXACT STOP, NON-MODAL
G10	PROGRAMMABLE OFFSET SETTING (X,Z,U,W,L,P,Q,R)
G14	MAIN-SPINDLE SHIFT TO SUB-SPINDLE
G15	MAIN-SPINDLE SHIFT TO SUB-SPINDLE CANCEL
G17	CIRCULAR MOTION XY PLANE SELECTION (G02,G03) (LIVE TOOLING)

G18	CIRCULAR MOTION ZX PLANE SELECTION (G02,G03) (SETTING 56)
G19	CIRCULAR MOTION YZ PLANE SELECTION (G02,G03) (LIVE TOOLING)
G20	VERIFY INCH COORDINATE POSITIONING
G21	VERIFY METRIC COORDINATE POSITIONING
G28	MACHINE ZERO RETURN THROUGH REFERENCE POINT (X,Z,U,W,B)
G29	MOVE TO LOCATION THROUGH G29 REFERENCE POINT (X,Z)
G31	FEED UNTIL SKIP FUNCTION (X,Z,U,W,F)
G32	THREAD CUTTING PATH, MODAL (X,Z,U,W,F)
G40	TOOL NOSE COMPENSATION CANCEL G41/G42 (X,Z,U,W,I,K) (SETTING 56)
G41	TOOL NOSE COMPENSATION, LEFT (X,Z,U,W) (SETTING 43, 44, 58)
G42	TOOL NOSE COMPENSATION, RIGHT (X,Z,U,W) (SETTING 43, 44, 58)
G50	SPINDLE SPEED MAXIMUM RPM LIMIT (S)
G51	RETURN TO MACHINE ZERO, CANCEL OFFSET
G52	WORK OFFSET COORDINATE POSITIONING
G52	GLOBAL WORK COORDINATE SYSTEM SHIFT
G53	MACHINE COORDINATE POSITIONING, NON-MODAL (X,Z,B)
G54	WORK OFFSET COORDINATE POSITIONING #1 (SETTING 56)
G55	WORK OFFSET COORDINATE POSITIONING #2
G56	WORK OFFSET COORDINATE POSITIONING #3
G57	WORK OFFSET COORDINATE POSITIONING #4
G58	WORK OFFSET COORDINATE POSITIONING #5
G59	WORK OFFSET COORDINATE POSITIONING #6
G61	EXACT STOP, MODAL (X,Z)
G64	EXACT STOP G61 CANCEL (SETTING 56)
G65	MACRO SUB-ROUTINE CALL

G70	FINISHING CYCLE (P,Q)
G71	OUTER-DIAMETER/INNER-DIAMETER STOCK REMOVAL CYCLE (P,Q,U,W,I,K,D,S,T,R1,F)
G72	END FACE STOCK REMOVAL CYCLE (P,Q,U,W,I,K,D,S,T,R1,F)
G73	IRREGULAR PATH STOCK REMOVAL CYCLE (P,Q,U,W,I,K,D,S,T,F)
G74	FACE GROOVING; HIGH SPEED PECK DRILL CYCLE (X,Z,U,W,I,K,D,F)
G75	OUTER-DIAMETER/INNER-DIAMETER PECK GROOVING CYCLE, (X,Z,U,W,I,K,D,F)
G76	THREAD CUTTING CYCLE, MULTIPLE PASS (X,Z,U,W,I,K,A,D,F)
G77	FLATTING CYCLE (I,J,L,R,S,K) (LIVE TOOLING)
G80	CANCEL CANNED CYCLE (SETTING 56)
G81	DRILL CANNED CYCLE (X,Z,W,R,F)
G82	SPOT DRILL / COUNTERBORE CANNED CYCLE (X,Z,W,P,R,F)
G83	PECK DRILLING CANNED CYCLE (X,Z,W,I,J,K,Q,P,R,F)
G84	TAPPING CANNED CYCLE (X,Z,W,R,F)
G85	BORE IN, BORE OUT CANNED CYCLE (X,Z,U,W,R,L,F)
G86	BORE IN, STOP, RAPID OUT CANNED CYCLE (X,Z,U,W,R,L,F)
G87	BORE IN, STOP, MANUAL RETRACT CANNED CYCLE (X,Z,U,W,R,L,F)
G88	BORE IN, DWELL, MANUAL RETRACT CANNED CYCLE (X,Z,U,W,P,R,L,F)
G89	BORE IN, DWELL, BORE OUT CANNED CYCLE (X,Z,U,W,P,R,L,F)
G90	OUTER-DIAMETER/INNER-DIAMETER TURNING CYCLE, MODAL (X,Z,U,W,I,F)
G92	THREADING CYCLE, MODAL (X,Z,U,W,I,F)
G94	END FACING CYCLE, MODAL (X,Z,U,W,K,F)
G95	END FACE LIVE TOOLING RIGID TAP (X,Z,W,R,F)
G96	CONSTANT SURFACE SPEED, CSS ON (S)
G97	CONSTANT NON-VARYING SPINDLE SPEED, CSS OFF (S)
G98	FEED PER MINUTE (F)

G99	FEED PER REVOLUTION (F)
G100	MIRROR IMAGE CANCEL G101
G101	MIRROR IMAGE (X,Z)
G102	PROGRAMMABLE OUTPUT TO RS-232 (X,Z)
G103	LIMIT BLOCK LOOKAHEAD (P0 - P15)
G105	SERVO BAR COMMAND
G110-111	WORK OFFSET COORDINATE POSITIONING
G112	CARTESIAN TO POLAR TRANSFORMATION
G113	CARTESIAN TO POLAR TRANSFORMATION CANCEL
G114-129	WORK OFFSET COORDINATE POSITIONING
G159	BACKGROUND PICKUP/PART RETURN
G160	APL AXIS COMMAND MODE ON
G161	APL AXIS COMMAND MODE OFF
G184	REVERSE TAPPING CANNED CYCLE (X,Z,W,R,F)
G187	ACCURACY CONTROL FOR HIGH SPEED MACHINING (E)
G194	SUB-SPINDLE / TAPPING CANNED CYCLE
G195	LIVE TOOLING VECTOR TAPPING (X,F)
G196	LIVE TOOLING VECTOR TAPPING REVERSE (X,F)
G200	INDEX ON THE FLY (X,Z,U,W,T)

Lathe G-Code

Commonly Used "G" Codes - CNC Lathe	
G00 - Rapid Positioning	G57 - Workpiece Coordinate Setting #4
G01 - Feedrate Positioning	G58 - Workpiece Coordinate Setting #5
G02 - Arc Clockwise	G59 - Workpiece Coordinate Setting #6
G03 - Arc Counterclockwise	G61 - Exact Stop Check Mode
G04 - Dwell	G62 - Automatic Corner Override

G07 - Feedrate Sine Curve Control	G63 - Tapping Mode
G10 - Data Setting	G64 - Cutting Mode
G11 - Data Setting Cancel	G65 - User Macro Call
G17 - X - Y Plane	G66 - User Macro Call (Modal)
G18 - X - Z Plane	G67 - User Macro Call Cancel (Modal)
G19 - Y - Z Plane	G70 - Finishing Cycle
G20 - Inch Units	G71 - Turning Cycle
G21 - Metric Units	G72 - Facing Cycle
G22 - Stored Stroke Check ON	G73 - Pattern Repeat
G23 - Stored Stroke Check OFF	G74 - Drilling Cycle
G27 - Reference Point Return Check	G75 - Grooving Cycle
G28 - Automatic Zero Return	G76 - Threading Cycle
G29 - Return from Zero Position	G80 - Canned Cycle Cancel
G30 - 2nd Reference Point Return	G83 - Face Drilling Cycle
G31 - Skip Function	G84 - Face Tapping Cycle
G32 - Thread Cutting	G86 - Face Boring Cycle
G36 - Automatic Tool Compensation	G90 - Absolute Positioning
G40 - Tool Compensation Cancel	G91 - Incremental Positioning
G41 - Tool Compensation Left	G92 - OD Thread Cutting Cycle
G42 - Tool Compensation Right	G94 - Face Turning Cycle
G46 - Automatic Tool Compensation	G96 - Constant Speed Control
G50 - Coordinate System Setting	G97 - Constant Speed Control Cancel

G52 - Local Coordinate System Setting	G98 - Feedrate Per Time
G53 - Machine Coordinate System Setting	G99 - Feedrate Per Revolution
G54 - Workpiece Coordinate Setting #1	G107 - Cylindrical Interpolation
G55 - Workpiece Coordinate Setting #2	G112 - Polar Coordinate Interpolation
G56 - Workpiece Coordinate Setting #3	G113 - Polar Coordinate Interpolation Cancel

M-Code for Lathes and Mills

Commonly Used "M" Codes - Mill & Lathe	
Mill	Lathe
M00 - Program Stop	M00 - Program Stop
M01 - Optional Stop	M01 - Optional Program Stop
M02 - Program End	M02 - Program End
M03 - Spindle Clockwise	M03 - Spindle Clockwise
M04 - Spindle Counter Clockwise	M04 - Spindle Counter Clockwise
M05 - Spindle Stop	M05 - Spindle Stop
M06 - Tool Change	
M07 - Thru Spindle Coolant ON	M07 - Flood Coolant #1 On
M08 - Flood Coolant ON	M08 - Flood Coolant #2 On
M09 - Coolant Off (all coolant)	M09 - Coolant Off
M10 - Table Pallet Clamp	
M11 - Table Pallet Unclamp	

M12 - Shower Coolant On	
M14 - Spindle Air Blow On	
M15 - Spindle Air Blow Off	
M16 - Air Blast / Tool Changer	
M18 - Air Blast Off	
M19 - Spindle Orientation	
M29 - Rigid Tapping	
M30 - End Program	M30 - End Progarm
M60 - Pallet Change	
M61 - Load Pallet #1	
M62 - Load Pallet #2	
M98 - Sub Program Call	M98 - Sub Program Call
M99 - Sub Program Cancel	M99 - Sub Program Cancel