A Power Assessment of Machining Tools

by

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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2002

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Abstract

Energy conservation is becoming a more important ideal in today's society, due to the increasing awareness of environmental and economic impacts. This project experimentally measures the power consumption, which is related to the energy consumption, of machines in the Laboratory for Manufacturing and Productivity, in order to determine the energy cost of the machines. This project then compares the results found experimentally to the theoretical minimum energy consumption in order to reference the measurements to the ideal energy consumption. Finally, this project attempts to find documentation of these energy costs in order to project the results found experimentally onto machines not physically available for measurement. This project found that the machines in the Laboratory for Manufacturing and Productivity used more energy than was necessary while running, due to the sometimes large amount of power needed to run the idle machines. The specifications given by the machine's manufacturers were adequate to estimate the maximum power requirements. Combining these estimates with the motor properties allowed one to estimate the power requirements of both unloaded operation (while the machine was idle) as well as loaded operation.

Thesis Supervisor: Timothy G. Gutowski
Title: Professor
Acknowledgments

I would like to thank the following people: Professor Gutowski for making this topic of research available; David Dow and Mark Belanger for working through the tests with me; and Gerald Wentworth for allowing me the use of the Laboratory for Manufacturing and Productivity.
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Chapter 1

Introduction

In today's society, the conservation of energy is becoming an important idea in manufacturing. It is important because the cost of energy keeps increasing. The cost of operating a piece of machinery is in part based upon the energy that it consumes. That energy is becoming more and more expensive every day. Energy sources that were once cheap through the overabundance of natural resources such as coal and oil are becoming expensive as society realized the limitations of these resources. This gives society, which must produce goods via energy at the lowest cost possible, as well as preserve energy resources for later generations, the task of minimizing energy use.

In manufacturing, much energy goes into the production of useful goods. The production of a good can be broken down into many steps, with each step requiring an amount of energy. This energy is due to two factors: the power consumed by the machine, and the time that the machine takes in completing the step. The power is a function of time dictated by the following equation:

\[ P = \frac{dE}{dt} \]  \hspace{1cm} (1.1)

If, as many machines are, the machine depends upon electricity to receive its power, then the power may be characterized by two other variables: the voltage applied over the electrical connection and the current supplied. An analogy to voltage and current
is a stream of cold water. The voltage would be the temperature of the water, i.e. how much colder the water is from the environment. The current would be how much water is flowing. For the stream, the heat transfer, which is analogous to the power flowing through the electrical connection, is a product of both the temperature and the amount of water flowing by. The mathematical relationship between the power, $P$, transmitted and the voltage, $V$, and current, $I$, through the electrical connection is given by the following equation:

$$ P = V \times I. $$

It should be noted that in typical electrical connections, the voltage supplied (e.g. the temperature of the water) remains constant, while the current draw varies over the time of the process. The greater the current draw through the electrical connection at a constant voltage, the more power is being drawn. This relationship will allow us to analyze the power consumption of various steps in the manufacturing process.

Each step in the process requires a specific amount of energy to complete. However, each step is not performed with the same regularity as others. Some steps may be done once per part produced, while others may happen only once each time the machine starts up. Furthermore, some processes of the system may last the entire length that the machine is powered on, while other processes may last only a portion of the part's actual production time. An example of an injection-molding machine follows that shows the breakdown of energy requirements for the manufacturing of a mold.

The injection-molding machine injects molten plastic into a mold piece. The plastic then cools, as it is packed into the mold. The result is a plastic part, that resembles the mold piece interior. The entire process can be broken down into smaller individual processes from the moment the machine is turned on to the moment the part exits the mold as shown in Figure 1-1. When the machine is turned on, the computer and fans start up, creating an initial power draw. The computer and fans then run for the entire time that the machine is on. Next, the heaters are turned on,
which heat the plastic pellets and cause them to melt. This process has an initial power draw while the heaters warm up. After the heaters have finished heating, they have a smaller power draw, while the heaters keep the plastic at a constant temperature. This latter power draw is present until the heaters are turned off, after the part has been removed. After the heaters have warmed up, the hydraulic motors are started, which controls the feed screw (in charge of injecting the molten plastic into the mold). The initial power draw of this is low, as the idle pressure of the machine is only about 145psi, however during the feed process the power draw increases as the pressure increases.

Figure 1-1: The step-by-step illustration of an injection-molding machine going through the process of turning on, and then creating a part. The heaters take a large amount of power during the “startup” phase as they heat the plastic pellets up. After the initial heat-up, the power requirement of the heaters decreases.

The machine is now in the “on” state, and is ready to start the actual process of making the part. This process can be broken down into stages: the clamping stage, the feed stage, the cooling & packing stage, and the unclamping stage. Each of these stages requires a power draw, with the clamping stage requiring the largest power draw of the entire process. However, unlike the power draws associated with turning the machine on, these power draws are only realized when the machine is producing a part. Per-part power draw is more advantageous than the steady power draw of turning the machine on because it only happens when the machine is in production,
i.e. when the machine is making money. There is less “waste” energy during the production process because when the machine is on, but not producing parts, the power draw is not going to the manufacture of goods; instead it is entirely wasted.

Waste energy is the energy consumed by the machine that does not go into the formation of the part. Furthermore, during the actual production of parts, energy is lost through many different ways. For example, during the heating process, the heater does not only heat the plastic, but heats the environment as well. This results in energy that does not go into the production of the part, but that is lost to the environment. Other losses include heated plastic that is not injected into the mold and the excess clamping pressure beyond that absolutely needed to keep the mold pressed together.

The minimum energy needed to create the product can be calculated by taking the mass of plastic needed for one part and determining the energy needed to first heat the plastic to liquid form, then transition it into the shape of the part, and finally the energy to cool the part. Thus, the energy wasted in the actual production of the part is the difference between the energy used in production and the energy calculated for the production of the part.

Utilizing these techniques to determine the way that machines use power, one can begin to look at the energy cost of a machine. By finding new ways to do certain tasks of a process, one can find the best power scheme that minimizes the power input while maximizing the power output to the part. This would not only reduce the waste energy being exhausted to the environment, but also be a better monetary solution as well, because saving power during production can lead to a cheaper cost of the part. However, before one can attempt to reduce the waste energy used in production machines, the machine must be properly analyzed, in order to determine where energy is both used, and where it is wasted. This requires a look at the procedures involved to physically measure the machine.
1.1 Measuring Machining Tools

The Laboratory for Manufacturing and Productivity at MIT provides an ideal environment for setting up a procedure to measure the power input required by machines. The lab hosts a variety of machines used in many different manufacturing environments, and the machines are available for general testing to students. This project analyzed the power requirements of six (6) machines in the lab, in order to both determine a general procedure for measuring the power requirements of the machines during various stages of operation, as well as determine the range of power requirements expected for varying types of machines. Specifically, this project analyzed the machines found in Table 1.1 below. Each machine’s power requirements were analyzed while idling as well as under various loads, in order to determine the power consumption of the different components within the machine.

<table>
<thead>
<tr>
<th>Type</th>
<th>Company</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Molding Machine</td>
<td>Engel</td>
<td>30</td>
</tr>
<tr>
<td>Manual Milling Machine</td>
<td>Bridgeport</td>
<td>Series I Standard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor Model: F-5-09-355</td>
</tr>
<tr>
<td>Manual Milling Machine</td>
<td>Bridgeport</td>
<td>Series I Standard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor Model: 6-X005</td>
</tr>
<tr>
<td>Automated Milling Machine</td>
<td>Bridgeport</td>
<td>Torq-Cut TC3</td>
</tr>
<tr>
<td>Automated Milling Machine</td>
<td>Cincinnati Milacron</td>
<td>7VC</td>
</tr>
<tr>
<td>Automated Lathe Machine</td>
<td>DaeWoo</td>
<td>Puma 8HC-3A</td>
</tr>
</tbody>
</table>

Table 1.1: Machines in the Laboratory for Manufacturing and Productivity at MIT that are analyzed in this project.

The cuts performed all used cutting-fluid throughout the process. Cutting-fluid affects the machining in the following ways: [9]

- Reduces friction between the cutting tool and the part
- Reduces energy consumption
- Cools the part
- Washes away the chips
- Protects the part from corrosion

If cutting fluid were not used, then the chips would become loaded along the cut, which would add to the overall load on the tool, making the cut more power consuming than if there were no chip loading. Although the goal of this project is to put the machines under load, the chip load was not predictable, due to the variability of when and how the chips pile up along the wall of the cut. In order to make meaningful measurements of the power consumption during cuts, it was necessary to make clean cuts on the aluminum. This necessitated the use of cutting-fluid for the cuts.

The machines were loaded by performing cuts on 6061-T6 Aluminum, which is a composite of various metals, as shown in Table 1.2 [2]. This aluminum alloy is moderately easy to machine compared to other aluminum alloys, and it was chosen due to its availability. The milling machines (both automatic and manual) made facing cuts on the aluminum blocks, using an end mill. The end mill cut a “trench” into the aluminum block, as shown in Figure 1-2. Thus the width of cut was the same as the tool diameter. The lathe also used 6061-T6 Aluminum, however it made facing cuts on an aluminum cylinder with a facing/turning tool, where the amount of material removed was kept constant.

<table>
<thead>
<tr>
<th>Component</th>
<th>Percent Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>98.00</td>
</tr>
<tr>
<td>Cr</td>
<td>0.04-0.35</td>
</tr>
<tr>
<td>Cu</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>Fe</td>
<td>Max 0.70</td>
</tr>
<tr>
<td>Mg</td>
<td>0.8-1.20</td>
</tr>
<tr>
<td>Mn</td>
<td>Max 0.15</td>
</tr>
<tr>
<td>Si</td>
<td>0.40-0.80</td>
</tr>
<tr>
<td>Ti</td>
<td>Max 0.15</td>
</tr>
<tr>
<td>Zn</td>
<td>Max 0.25</td>
</tr>
</tbody>
</table>

Table 1.2: Material makeup of 6061-T6 Aluminum. This aluminum is a moderately malleable alloy compared to other aluminum alloys.

By varying the material removal rate (MRR) on the 6061-T6 Aluminum, the load on the machine could be varied in order to measure the power requirements of the
Figure 1-2: A 6061-T6 Aluminum block machined with a 2\(\text{in}\) facing cut by an end mill. The width of the cut is equal to the diameter of the tool used.

machine. This was used to create the results obtained in the following chapters. However, before looking at the results, it is necessary to explain the tools used in experimentally determining the power consumption of the machines.
Chapter 2

Procedures for Measuring Power Consumption of Machines

In order to measure the power consumption of the machines in the Laboratory for Manufacturing and Productivity, it is necessary to first understand how power flows through the machines. Using the Bridgeport manual milling machines as a simple example, the power cord is hooked up to the motor as shown in Figure 2-1. The Bridgeport uses a three-phase motor, as can be seen by the number of connection boxes shown in the Figure 2-1; three columns of connections, with each row having a positive and negative column.

Figure 2-2 shows a typical power connection diagram for a 3-phase motor. The three leads coming in to the motor (marked N) each carry a certain voltage and charge. The A and B leads carry an equal voltage, \( V_{AC} = V_{BC} = V \), and current, \( i_A = -i_B = i \), while the C lead carries a ground signal, \( V_C = 0 \) and \( i_C = 0 \). [1]

The voltage going to the motor is the sum of the voltages from the leads, in this case the addition of \( V_{AC} \) and \( V_{BC} \), or \( 2V \). The current running through the A and B wires is the current going to the motor, because the leads are parallel to each other. Because the C wire is grounded, there necessarily must be no current flow through it. [1]

In order to physically measure the voltage or current running through a machine, one must use a tool capable of measuring these properties. One such tool is a multime-
Figure 2-1: The electrical connection of the Bridgeport manual milling machine's three-phase motor to the power cord. Note the three columns of connections, each with a positive and negative row.

Figure 2-2: A typical power diagram for a three phase motor. The $A$ and $B$ wires carry an equal current and voltage while the $C$ wire is grounded (i.e. it has no current and zero voltage).
ter, which has the ability to measure either voltage, current, or resistance depending upon the configuration in which it is set up to do. Another tool is a clamp-on multimeter, which also has the ability to measure the current and voltage running through a circuit without physically touching the wires. Both of these tools are very useful in carrying out measurements, however they use very different properties to carry out the measurements.

2.1 The Multimeter

The multimeter, shown in Figure 2-3, has three modes of operation – it can measure voltage as a voltmeter, current as an ammeter, or resistance as an ohmmeter. To measure the power, as was shown in Chapter 1, the resistance does not need to be known; however the voltage and current of the system are required. To switch between modes, there is a dial as shown in Figure 2-3. One must be sure that the multimeter is in the correct mode to measure either the voltage or the current. Inability to follow this will result in potential damage to the multimeter, the machine being measured, and the person performing the measurement!

As a voltmeter, the multimeter can measure the voltage running through the motor in Figure 2-1. The voltage can be determined by the sum of the voltages across wires, as shown in Figure 2-2. By measuring the voltage difference between the ground and the two other leads, the multimeter can determine the voltage of the system. The multimeter connects to both leads in its measurement, in order to measure the difference between two wires (usually a “hot” wire and the “ground” wire, e.g. $V_{AC}$ or $V_{BC}$). By connecting the two wires together through the multimeter, the multimeter effectively creates a second circuit. If the resistance inside of the multimeter is too low, the current through the circuit will “prefer” the path of the multimeter. This leads to a large amount of current traveling through a low resistance wire, creating large amounts of heat and usually blowing out the entire circuit. This is called a short-circuit. The multimeter prevents this from happening by having a very large internal resistance (appreciably infinite). This prevents much current to flow between
Figure 2-3: The Multimeter. The dial controls what the multimeter should measure: voltage, current, or resistance. The leads coming from the bottom of the multimeter physically connect with the wire(s) to measure the selected variable.

As an ammeter, the multimeter can measure the current running to the motor. This is done, not by connecting the multimeter to different wires, but by bridging one of the wires with the multimeter. This is done by creating a gap in one of the wires; e.g. by unscrewing the wire from one of the leads in Figure 2-1 and connecting either end of the multimeter to the end of the wire and to the connection. By completing the circuit with the multimeter, the multimeter has the current of the wire flow through the multimeter, allowing it to measure the current flowing through the motor. Unlike its role as a voltmeter, while the multimeter acts as an ammeter its internal resistance is very low (appreciably zero) in order to allow the current to freely flow through the multimeter and not disturb the system. [3]

If the multimeter were to be configured as an ammeter, but hooked up as a voltmeter, then the multimeter would cause damage to the machine. This is because
the ammeter would have a very low internal resistance and a large voltage drop through the ammeter, thereby short-circuiting the entire machine. One the other hand, if the multimeter were to be configured as a voltmeter, but hooked up as a ammeter, the machine would stop functioning, as current would not be allowed to flow through the high-resistance multimeter into the motor. At best, these results would not be correct; at worst, the multimeter could harm the machine and/or the individual.

2.2 Clamp-On Multimeter

Clamp-On multimeters, such as the Amprobe® RC-1 shown in Figure 2-4, can measure the current and voltage in a wire as well. [14] Unlike regular multimeters though, clamp-on multimeters rely on the Hall Effect in order to determine the voltage and current running in a wire. By creating a magnetic field around the wire, the clamp-on multimeter can measure the resulting force caused by the current flow in the wire. Thus, without physically touching the wire, the clamp-on multimeter can measure the current and voltage in the wire. [11]

The clamp-on multimeter is a much safer alternative to the standard multimeter. By not touching or exposing the wires, there is less opportunity for the wires to touch each other and create short-circuits. Also, there is less opportunity for the person measuring to touch the wires, and shock himself. The clamp-on multimeter creates a safe environment in which to measure the current and voltage needed by machines, and is thus the clear choice for the high current/high voltage measurements done in this project.
Figure 2-4: The Amprobe®. Through the Hall Effect, the clamp-on multimeter measures the current and voltage in a wire without physically touching the wire. Instead, the clamp-on multimeter creates a magnetic field around the wire, and measures the resulting force created by the Hall Effect.
Chapter 3

Profiling the Power Consumption of the Machines Through Experimentation

Determining the power consumption of the machines in the Laboratory for Manufacturing and Productivity required a certain procedure in order to correctly and accurately measure the overall power draw on the machines. The procedure can be broken up into individual steps needed to measure the power consumption. The first step is to locate a place to measure the current flowing into the machine from the wire. The second step is to measure the current during the different stages of the startup of the machine. The third step is to measure the current during different run time operations that the machine does, if any (e.g. the injection phase of the injection-molding machine). The fourth step is to measure the current while the machine is in production (i.e. while the machine has a load applied). These steps, common to the six machines measured, vary in implementation amongst the machines. Thus, it is best to examine each machine individually and look at how these steps were carried out. Afterwards, comparisons between the machines can be made in regard to the power consumption measured in each.
3.1 Engel 30 Injection Molding Machine

![Image of Engel 30 Injection Molding Machine]

Figure 3-1: The Engel 30 Injection-Molding Machine forms plastic parts by melting plastic pellets and injecting them into a preset mold.

The Engel 30, as shown in Figure 3-1, is used to create plastic parts from mold blanks. It has a hydraulic motor, which has a total rated power of 10hp \([7]\). It runs on a 480V power connection, running into a transformer that converts the 60Hz AC signal in the wall outlet to a 50Hz AC signal required by the machine. This change is required because the machine, made in England, does not run off a standard US power source running at 60Hz. The power cable is shielded until it reaches the transformer, and therefore one must hook the Amprobe\(^\circ\) on the transformer itself in order to accurately measure the current going into the machine. This is located in the lower-right hand cabinet of the machine shown in Figure 3-1. By connecting the Amprobe\(^\circ\) to the wires coming directly into the transformer, measurements of the current were taken.

Table 3.1 shows the results of the measurements taken. The current measurements were converted into power using Equation 1.2. The first set of measurements
describe the individual systems as they came on – first the transformer, second the computer and fans, third the heaters (which required more power during the heat up of approximately 30 minutes prior to the machine being ready to produce parts), and finally the hydraulic motors controlling the feed and injection of the plastic pellets into the mold, as well as the clamping force holding the mold together. Once the machine was on, the second set of measurements in Table 3.1 show the varying run-time operations. These runtime operations include constant power consumptions such as the feed process and the injection process, which use the same amount of power each time they are invoked, as well as variable power consumptions such as the clamping force, where the power consumption is determined by the pressure of the clamp. The Engel can apply a maximum pressure of 30tons. Figure 3-2 graphs the startup power consumption, the constant power consumption after the Engel has warmed up, and the power consumption during a period where the Engel exerts a 30 ton clamping force, illustrating the proportions of each stage’s consumption of power.

<table>
<thead>
<tr>
<th>Process</th>
<th>Power Consumption (W)</th>
<th>Percentage of Total Power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>580</td>
<td>1.2</td>
</tr>
<tr>
<td>Computer and Fans</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>Heaters (Startup)*</td>
<td>2060</td>
<td>4.3</td>
</tr>
<tr>
<td>Heaters (Steady-State)</td>
<td>530</td>
<td>1.1</td>
</tr>
<tr>
<td>Unloaded Hydraulic Motors</td>
<td>2690</td>
<td>25.6</td>
</tr>
<tr>
<td>Feed Process</td>
<td>620</td>
<td>5.9</td>
</tr>
<tr>
<td>Injection Process</td>
<td>770</td>
<td>7.3</td>
</tr>
<tr>
<td>Clamping Process</td>
<td>5280</td>
<td>50.2</td>
</tr>
<tr>
<td>30tons (maximum allowed)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*:This value represents the startup power draw of the heaters, which is higher than the steady-state power draw, because more power is needed to initially melt the plastic pellets than to keep the pellets at the desired temperature.

Table 3.1: The individual stages of the Engel 30 Injection-Molding Machine, and the power requirements of each stage. The Clamping Process requires a variable amount of power, dependent on the clamping pressure exerted.

These results are shown graphically in more detail in Appendix A Figure A-1. It is important to note that the clamping force varies linearly with load, from 0tons of
Figure 3-2: A bar graph illustrating the proportional power consumption of startup, idle, and runtime power consumption for the Engel 30 Injection Molding Machine.

force to a physical maximum 30tons of force. For most products, the 30tons of force will not be used, and a reasonable assumption of 15tons of force is an acceptable figure for most processes. Furthermore, the clamping force is not applied over a large amount of time – only about 4 to 5 seconds of a process taking about a minute to complete. Thus, the energy required is proportionally lower with respect to the other stages of the system than the power required for clamping.

There are many different variables associated with the time a part will take in the various stages of operation in the injection molding machine. The amount of plastic to be injected will affect every part of the injection-molding process, from the time of injection, the pressure imposed by the clamping, to the cooling time of the part before it can be removed. The shape of the mold also affects many variables, from the packing time and re-packing time, to the injection time. It is impossible to create a generalized number that represents the actual energy used in the creation of a part. Rather, it is more important to look at the general time intervals combined with the power consumption measurements. Processes that take a long amount of time yet
consume little power, like the injection and packing stages might be as important as processes that take a short amount of time but a large amount of power, like the clamping stage. Stages that must always be on, that is, whether the machine is making a part or not, are most often very important energy consumers, because by reducing them, the energy associated in the run of a batch of parts can be significantly reduced.
3.2 Bridgeport Manual Milling Machines

Figure 3-3: The Bridgeport Manual Milling Machine lacks the automation found in the Injection Molding Machine. The user controls all aspects of the machining manually. Motors only run the drill and automate the x-axis bench movement, which are both independent of each other with regards to their power source.

The two Bridgeport Manual Milling Machines analyzed in this project were very similar to each other. One of the two Bridgeports is pictured above in Figure 3-3. Both Bridgeports had almost identical properties. Both had the motors with the same specifications: 2hp motors (maximum power output; 1.5hp continuous operation), fed from a 480V power supply. Thus, comparisons between the two Bridgeports will allow us to determine the reliability of our measurements between machines of the same make and model.

The Amprobe® was hooked up to the electrical box residing on the top of the machines as shown in Figure 3-3 with the black cable traveling from the ceiling into the box on left. This is shown more clearly in Figure 3-4. The machines were then started, first by turning on the computer system and next by starting up the spindle motor (running power to the motor in order to allow them to be controlled). Next,
the machines each did a series of cuts on a piece of 6061-T6 Aluminum. The cuts were all performed with the same 3-flute 2" diameter end mill spinning at 2300rpm spindle speed. The feed rate was set at $20 \text{ in. per min}$. Three different depths of cut were performed: 0.050", 0.100", and 0.150", which correspond to material removal rates (MRRs) of $5.46 \times 10^{-7} \text{ m}^3\text{s}^{-1}$, $10.92 \times 10^{-7} \text{ m}^3\text{s}^{-1}$, and $16.38 \times 10^{-7} \text{ m}^3\text{s}^{-1}$ respectively. The last cut pushed the machines to the very limit of what they were capable of doing, and caused one of the machine’s belt to stall on the cut due to the high load. With these cuts, the power consumption required by machining was assessed.

Figure 3-4: A close up of the electrical box where the Amprobe® was hooked up to take measurements of the Bridgeport Manual Milling Machine.

Table 3.2 shows the results of the measurements converted into power consumption. It is clear that the results are very similar to one another, showing that similar machines, especially machines of the same make and model, perform uniformly with regard to power consumption. Charts, showing the two Bridgeport Manual Milling
Machines’ power consumption can be found in Appendix A Figure A-2 and Figure A-3. It is clear that the Bridgeports are almost identical with regard to power consumption. Figure 3-5 and Figure 3-6 show bar graphs for the two machines’ power consumption. These both show the power consumption used while idle (denoted Constant) and while machining a piece of 6061-T6 Aluminum with a 1.638 cm³/s material removal rate.

<table>
<thead>
<tr>
<th>Power Consumption of Individual Stages (W)</th>
<th>Bridgeport (F-5-09-355)</th>
<th>Bridgeport (6-X005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Readout</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Unloaded Motors</td>
<td>530</td>
<td>580</td>
</tr>
<tr>
<td>Machining</td>
<td>1060</td>
<td>1340</td>
</tr>
<tr>
<td>MRR*: (5.46 \times 10^{-7} \text{m}^3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machining</td>
<td>1630</td>
<td>1680</td>
</tr>
<tr>
<td>MRR*: (10.92 \times 10^{-7} \text{m}^3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machining</td>
<td>2260 (stalled)</td>
<td>2350</td>
</tr>
<tr>
<td>MRR*: (16.38 \times 10^{-7} \text{m}^3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: MRR → Material Removal Rate

Table 3.2: Table comparing the two Bridgeport Manual Milling Machines’ power consumption. Both had similar motor properties, and both had similar measured power consumption properties as a result.

The manual milling machines have a much greater percentage of variable power consumption than the injection molding machine discussed earlier, or the automatic milling machines discussed later in the chapter. Furthermore, the power consumption as a whole for these machines is drastically lower than the automated machines, as little as a tenth as much power is drawn in some instances. This shows that the “cost” of automation lies in power consumption – the more a machine is able to do on its own, the more power it will require for the same activity. The automation and decrease in human labor must be weighed against the increased use of power by the machines, in order to determine the true benefit of the automated machines.
Figure 3-5: A bar graph illustrating the power consumption of idle and runtime power consumption for the Bridgeport Manual Milling Machine (motor model: F-5-09-355).

Figure 3-6: A bar graph illustrating the power consumption of idle and runtime power consumption for the Bridgeport Manual Milling Machine (motor model: 6-X005).
3.3 Bridgeport Torq-Cut TC3 Automated Milling Machine

Figure 3-7: The Bridgeport Torq-Cut TC3 Automated Milling Machine machines parts using a high-precision drill with many different end mills to both drill holes as well as machine surface areas.

The Bridgeport Torq-Cut represents the newest machine in the Laboratory for Manufacturing and Productivity. Manufactured in 1998, it runs at 230V, instead of the 480V that the Cincinnati Automated Milling Machine and Engel Injection-Molding Machine run at. Measuring the current into the Bridgeport required opening the large panel behind the machine, shown in Figure 3-7. There, the cable ran into the fuse box in the machine and was unshielded so that the Amprobe® could be used to measure the current.

The current was measured throughout the startup process, which involved turning on the computer and fans, the servos in charge of manipulating the clamps, spindle, and tool carousel, the coolant pump, the spindle key, and finally powering up the spindle motor. Next, the current was measured as the machine did various runtime
operations, including jogging the x/y/z axis of the platform on to which the piece was clamped, changing the cutting tools, moving the spindle up and down (z axis translation), and rotating the carousel. Finally, the current was measured while the 6061-T6 Aluminum block (the same as was used by the Bridgeport Manual Milling Machines) was machined. The aluminum block was machined using a 3-flute 3.15" diameter end mill, being fed at a 70 \( \frac{m}{min} \) feed rate at varying depths: 0.075", 0.150", and 0.200", which corresponded to material removal rates (MRRs) of \( 4.52 \times 10^{-6} m^3/s \), \( 9.03 \times 10^{-6} m^3/s \), and \( 13.55 \times 10^{-6} m^3/s \) respectively. The program that was used to create face milling cuts on the aluminum block at various depths is shown in Appendix B.1. The results of these measurements, converted into power consumption and percentage of total power, are located in Table 3.3 below.

<table>
<thead>
<tr>
<th>Process</th>
<th>Power Consumption (W)</th>
<th>Percentage of Total Power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer and Fans</td>
<td>410</td>
<td>5.9</td>
</tr>
<tr>
<td>Servos</td>
<td>90</td>
<td>1.3</td>
</tr>
<tr>
<td>Coolant Pump</td>
<td>140</td>
<td>2.0</td>
</tr>
<tr>
<td>Spindle Key</td>
<td>140</td>
<td>2.0</td>
</tr>
<tr>
<td>Unloaded Motors</td>
<td>140</td>
<td>2.0</td>
</tr>
<tr>
<td>Jog (x/y/z axis translation)</td>
<td>460</td>
<td>6.6</td>
</tr>
<tr>
<td>Tool Change</td>
<td>230</td>
<td>3.3</td>
</tr>
<tr>
<td>Spindle (z axis translation)</td>
<td>690</td>
<td>9.9</td>
</tr>
<tr>
<td>Carousel Rotation</td>
<td>90</td>
<td>1.3</td>
</tr>
<tr>
<td>Machining</td>
<td>2420</td>
<td>34.5</td>
</tr>
<tr>
<td>MRR*: ( 4.52 \times 10^{-6} m^3/s )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machining</td>
<td>&gt; 3570 (stalled)</td>
<td>51.0</td>
</tr>
<tr>
<td>MRR: ( 9.03 \times 10^{-6} m^3/s )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machining</td>
<td>&gt; 4600 (stalled)</td>
<td>65.8</td>
</tr>
<tr>
<td>MRR: ( 12.04 \times 10^{-6} m^3/s )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: MRR \rightarrow \text{Material Removal Rate}

Table 3.3: The individual stages of the Bridgeport Torq-Cut TC3 Automated Milling Machine, and the power requirements of each stage. The \textit{Machining} stage requires a variable amount of power, dependent on the load on the drill due to the cut.

Most of the power goes into the physical machining of the part, which means that when the machine is idle, there is a smaller percentage of power being wasted
than when most of the power went into keeping the machine on. Furthermore, the energy is directly dependent upon the time period of the cut. Energy consumption can be determined by finding the time it takes to perform the cut, and multiplying that by the power required to perform the cut (i.e. integrating Equation 1.1 gives the equation $P = Et$).

A graphical representation of the data in Table 3.3 can be found in Appendix A Figure A-4. Figure 3-8 shows a bar graph of the power consumption both while idle (denoted Constant) as well as while machining a piece of 6061-T6 Aluminum with a $12.04 \text{cm}^3/s$ material removal rate. It is clear that this machine spends most of its power consumption during the machining of the part.

![Figure 3-8: A bar graph illustrating the power consumption of idle and runtime power consumption for the Bridgeport Torq-Cut TC3 Automated Milling Machine.](image-url)
3.4 Cincinnati Milacron 7VC Automated Milling Machine

Figure 3-9: The Cincinnati Milacron 7VC Automated Milling Machine produces parts similar to the Bridgeport Torq-Cut. It runs at 480V instead of the Bridgeport’s 230V.

The Cincinnati Milacron 7VC Automated Milling Machine, shown in Figure 3-9, is ten years older than the Bridgeport Torq-Cut, having been built in 1988. Unlike the Torq-Cut, the Cincinnati runs at 480V. In order to measure the current of the machine, as in the Torq-Cut, the cabinet holding the internal fuse box was opened. This cabinet is located on the right side of the machine. The wires leading into the fuses were accessible via a ladder due to the height of the fuse box. The Cincinnati performed the same cuts as the Torq-Cut, and the results of the power consumption measurements are shown along with the power output in Table 3.4 below.

A graphical representation of Table 3.4 can be found in Appendix A Figure A-5. Compared to the Torq-Cut, the Cincinnati requires more power to make the same cuts. A greater amount of power consumption of the Cincinnati goes into the running of the machine. That means that when the machine is idle and on, for
<table>
<thead>
<tr>
<th>Process</th>
<th>Power Consumption (W)</th>
<th>Percentage of Total Power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer and Fans</td>
<td>1680</td>
<td>13.5</td>
</tr>
<tr>
<td>Servos</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>Coolant Pump</td>
<td>1200</td>
<td>9.6</td>
</tr>
<tr>
<td>Spindle Key</td>
<td>140</td>
<td>1.2</td>
</tr>
<tr>
<td>Unloaded Motors</td>
<td>340</td>
<td>2.7</td>
</tr>
<tr>
<td>Jog (x/y/z axis translation)</td>
<td>960</td>
<td>7.7</td>
</tr>
<tr>
<td>Tool Change</td>
<td>480</td>
<td>3.8</td>
</tr>
<tr>
<td>Spindle (z axis translation)</td>
<td>1440</td>
<td>11.5</td>
</tr>
<tr>
<td>Carousel Rotation</td>
<td>240</td>
<td>1.9</td>
</tr>
<tr>
<td>Machining</td>
<td>2400</td>
<td>19.2</td>
</tr>
<tr>
<td>MRR*: $4.51 \times 10^{-6}$ m$^3$ x$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machining</td>
<td>4800</td>
<td>38.5</td>
</tr>
<tr>
<td>MRR: $9.03 \times 10^{-6}$ m$^3$ x$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machining</td>
<td>6000</td>
<td>48.1</td>
</tr>
<tr>
<td>MRR: $12.04 \times 10^{-6}$ m$^3$ x$^{-1}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: MRR → Material Removal Rate

Table 3.4: The individual stages of the Cincinnati Milacron 7VC Automated Milling Machine, and the power requirements of each stage. The *Machining* requires a variable amount of power, dependent on the load on the tool due to the cut.
example when idling between parts, the Cincinnati is wasting more power (as well as a greater percentage) than the Torq-Cut would under the same circumstances. Figure 3-10 confirms that the Cincinnati uses a greater amount of power while idling and a smaller percentage of its power consumption for actual machining than the Torq-Cut.

![Bar chart](image)

Figure 3-10: A bar chart illustrating the power consumption of idle and runtime power consumption for the Cincinnati Milacron 7VC Automated Milling Machine.

Automated milling machines have made power-saving advancements since the production of the Cincinnati Milacron 7VC. Newer machines use less power, because they come equipped with more efficient motors, able to handle large loads without being as power-hungry as the larger motors used in the past. The Torq-Cut has a 9.5hp (peak power) motor [10] whereas the Cincinnati Milacron 7VC has a larger 10hp (peak power) motor [5] (the continuous power output of the motors is actually smaller than the advertised power), yet the Torq-Cut still outperforms the 7VC with regard to power consumption. Also, a greater part of the power consumption happens during the production of parts, rather than the general running of the machine. This means that during idle and transition time, less power is lost or wasted. As these
machines continue to mature, this trend will continue, decreasing the idle time power consumption in proportion to the machining power consumption in Figure 3-10.
3.5 DaeWoo Puma 8HC-3A Automated Lathe

![DaeWoo Puma 8HC-3A Automated Lathe Machine](image)

Figure 3-11: The DaeWoo Puma 8HC-3A Automated Lathe Machine machines parts by spinning the part at high velocities in order to create circular cuts.

The DaeWoo Puma 8HC-3A Automated Lathe, shown in Figure 3-11, is quite different than the milling machines with regard to not only purpose, but also power consumption requirements. It has a 20hp spindle motor (maximum power - 15hp continuous power), which rotates the part while the tool remains motionless [6]. To measure the power consumption, the Amprobe® was connected inside the breaker box on the wall behind the DaeWoo, as it was easily accessible and offered a way to measure the current without physically opening the machine’s computer cabinet as with the Torq-Cut. The Amprobe®, once hooked up to the breaker box, measured the current of the system during various stages of startup and runtime. The startup processes included the powering of the computer and fans, the powering of the coolant pump, the powering of the servos in charge of locking the piece of aluminum in place, and warming up the motors.

Because the DaeWoo is a lathe, and not a mill, the 6061-T6 Aluminum used was
a cylinder 2.5" in diameter. The DaeWoo did three facing cuts on the block, one at a depth of 0.050", one at a depth of 0.100", and one at a depth of 0.150". These cuts were performed with a facing/turning tool. This type of cut was also quite different than the milling cuts performed. Physically, the tool only touched the piece at one point, instead of three as in the case of the milling machines. This put a load on the lathe that was significantly less than would have been experienced, had the cut on the lathe been a three-point contact like the milling machines. The program used to create these cuts can be found in Appendix B.2.

The DaeWoo performed the cuts at a constant feed rate of 600 surface feet per minute with a feed rate of $0.03\frac{ft}{min}$, at depths of 0.050" and 0.100". This allowed the machine to have constant material removal rate (MRR) throughout the cut, $3.54 \times 10^{-5} \frac{m^3}{s}$ and $3.54 \times 10^{-5} \frac{m^3}{s}$ respective to the two depths, which made the load experienced by the lathe due to the cut constant. The constant surface feed rate also meant that the spindle holding the piece was continuously accelerating, because as the tool cut inward into the aluminum cylinder, the radius of the piece decreased. The DaeWoo compensated for this decrease by increasing the angular rotational speed of the spindle. As the radius of the cut went to zero, the angular rotational speed approached infinity in order to maintain the constant surface feed rate. A maximum angular rotation of 4000rpm was used, so that when the spindle reached that rotational rate it would not attempt to speed up more. This rotational rate was reached fairly close to the center of the aluminum cylinder, allowing the constant surface feed rate to be measured for a large duration of the cut.

Table 3.5 shows the results of the measurements. Notice that in each case, the load does not affect the current draw noticeably. Instead, the act of accelerating the spindle outweighs the current draw of the load. This is important because it implies that whatever the cut that is being made, the power consumption of that cut will be approximately the same. To test the effect of acceleration on load several different spindle accelerations are plotted. Also plotted are the power requirements of the spindle spinning at several constant rotational speeds, in order to determine the power necessary to keep the aluminum cylinder spinning at a constant rotational
Table 3.5: The individual stages of the DaeWoo Automated Lathe Machine, and the power requirement of each stage. The *Spindle Acceleration* requires a variable amount of power, whereas the load on the tool did not affect the power requirement significantly.

The results are also broken down graphically in *Appendix A Figure A-6*. It is plain that most of the power during the manufacturing process goes into the acceleration of the spindle. *Figure 3-12* shows this as well, allowing one to see the relation between startup power requirements versus spindle acceleration power requirements.
Figure 3-12: A bar graph illustrating the power consumption while the machine is idle, while the spindle spins at a constant speed of 4000rpm, and while the spindle accelerates to 4000rpm for the DaeWoo Puma 8HC-3A Automatic Lathe.
Chapter 4

Analyzing the Theoretical Minimum Power Consumption For Machining

It is now worth determining the theoretical minimum amount of power used for performing the various cuts done in lab, in order to see the difference between this value and the load experienced by the machines. For the purposes of brevity, only the milling cuts will be analyzed, as the injection molding process is quite complex and dependent on many different variables. The milling machine provides a simple example from which one can apply the results to other machines.

As was stated before, the milling machines performed face cuts on a 6061-T6 Aluminum block. These face cuts were performed with a certain diameter tool, moving across the block at a certain constant feed rate and at a certain depth. Knowing these values, and the material properties of 6061-T6 Aluminum, it is possible to calculate the power required to make the cut (while traveling at the specified feed rate).

For machining the power required to make a cut is defined as

\[ P = F_c v, \]  

where \( P \) is the power required, \( F_c \) is the force of the cut on the tool, and \( v \) is the
velocity with which the tool is traveling. Next, the material removal rate, $MRR$, is defined as

$$MRR = vw_{t_o}, \quad (4.2)$$

where $w$ is the width of the cut and $t_o$ is the thickness of the cut (the depth of cut).

Combining these two equations yields

$$\frac{P}{MRR} = \frac{F_c}{wt_o}. \quad (4.3)$$

This equation describes the power needed to perform a cut per the material removal rate of the cut. This value, called the unit power, $K_p$, is a property of materials relating the power required to cut a material and the rate at which the material is being cut (it is alternatively called unit horsepower or specific energy). For 6061-T6 Aluminum this value is

$$\left(\frac{P}{MRR}\right)_{6061-T6Al} = 6.8 \times 10^8 \frac{J}{m^3} [12]. \quad (4.4)$$

Rearranging Equation 4.3 with Equation 4.4, an equation for $F_c$ can be found:

$$F_c = 6.8 \times 10^8 \frac{J}{m^3}wt_o, \quad (4.5)$$

and finally combining this with Equation 4.1 yields

$$P = 6.8 \times 10^8 \frac{J}{m^3}wt_o v, \quad (4.6)$$

which describes the power in terms of the material property of aluminum, the width of the cut, the depth of the cut, and the velocity of the tool. [9]

Chips created by machining have an affect on the unit power, $K_p$. As the thickness of the chips decrease in size, a larger correction factor must be applied to $K_p$. The thickness of the chip is directly related to the feed, $f$, which in turn is related to the feed rate, $v$, the number of flutes of the tool, $n$, and the spindle speed of the tool, $\Omega$:
The relationship between feed and the correction factor is shown in Figure 4-1. As the feed increases, the correction factor decreases log-rhythmically. There is no correction factor at approximately 0.012 in. [13]

\[ f = \frac{v}{n\omega} \]  \hspace{2cm} (4.7)

The cuts done by the manual milling machines were done with a 2" diameter 3-flute tool spinning at 2000 rpm, traveling with a velocity of 20 \( \frac{\text{in}}{\text{min}} \) at depths of 0.050", 0.100", and 0.150". From Equation 4.7, the feed is 0.003 \( \frac{\text{in}}{\text{rev}} \), which corresponds to a correction factor of about 1.3. The minimum power required to make these cuts is listed below in Table 4.1. The actual power required is also listed for each machine, in order to show the difference between the measurements and the theory. The most shallow cut was very accurate with the correction factor applied, however the deeper cuts were negatively affected by the correction factor. This could be due to the deeper cuts affecting the chip thickness.

The cuts done by the automatic milling machines were done with a 3.15" diameter 3-flute tool spinning at 2000 rpm, traveling with a velocity of 70 \( \frac{\text{in}}{\text{min}} \) at depths of 0.075", 0.150", and 0.200". From Equation 4.7, the feed is 0.012 \( \frac{\text{in}}{\text{rev}} \), which corresponds to a correction factor of 1.0. Table 4.2 shows the minimum power required to make these...
Material Removal Theoretical Power Bridgeport Bridgeport
Rate (MRR) (cm$^3$/s) Consumption (W) (F-5-09-355) (6-X005)
0.546 975 1060 1340
1.092 1950 1630 1680
1.638 2910 2260 (stalled) 2350

Table 4.1: Table comparing the two Bridgeport Manual Milling Machines' power consumption to the theoretical power consumption required to make the same cuts.

<table>
<thead>
<tr>
<th>Material Removal Rate (MRR) (cm$^3$/s)</th>
<th>Theoretical Power Consumption (W)</th>
<th>Bridgeport Torq-Cut TC3</th>
<th>Cincinnati Milacron 7VC-750</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.52</td>
<td>3070</td>
<td>3340</td>
<td>5760</td>
</tr>
<tr>
<td>9.03</td>
<td>6150</td>
<td>&gt; 4490 (stalled)</td>
<td>8160</td>
</tr>
<tr>
<td>12.04</td>
<td>8190</td>
<td>&gt; 5520 (stalled)</td>
<td>9360</td>
</tr>
</tbody>
</table>

Table 4.2: Table comparing the two automatic milling machines' power consumption to the theoretical power consumption required to make the same cuts.

cuts, along with the actual power used by the two automatic milling machines. The automated milling machines also require a larger amount of power to perform the cuts than theoretically possible. However, the Torq-Cut, while stalling on the two deeper cuts, is much closer to the theoretical power consumption values than the 7VC. The 7VC on the other hand, requires a much larger amount of power than the theoretical power consumption. This is mostly likely due to the relative age of the machines – the Torq-Cut, which is a much newer machine, is also much more efficient.

Table 4.2 shows that between the two automated milling machines both required more power than theoretically necessary to perform the facing cuts on the aluminum block. The Torq-Cut, which is the newer machine, required less power than the 7VC, implying that the Torq-Cut is more efficient than the older 7VC. Figure 4-2 shows the relative power consumption of the 7VC and Torq-Cut, as compared to the theoretical power consumption for the smallest rate of material removal, 4.52 cm$^3$/s (on which neither machine stalled). The 1998 Torq-Cut is clearly more efficient than the older 1988 7VC.
Figure 4-2: The theoretical power consumption required for a $4.52 \text{cm}^3$ material removal rate (MRR) as compared to the actual power consumption of the two automated milling machines, the newer Bridgeport Torq-Cut and the older Cincinnati Milacron 7VC.
Chapter 5

Power Consumption Through Published Specifications

Knowing how the machines in the Laboratory for Manufacturing and Productivity used power consumption is an important building block in creating a procedure to determine the energy cost of running machines in a lab. This knowledge begs the next question: is it possible to determine power consumption requirements without going through the testing of each machine. With this in mind, this project attempts to use the specifications provided by the manufacturers of the six machines analyzed in Chapter 3 in order to produce collaborating data about the power consumption.

5.1 Maximum Power Draw

*Figure 5-1* shows the specification plate attached to the Bridgeport Torq-Cut TC3. A spec-plate is standard on most machines used for machining, and allows the operator to see certain important parameters about the machine:

- **Voltage** feeding into the machine.
- **Number of Phases** that the motor has (usually three).
- **AC Power Frequency** at which the motor runs at (typically 60Hz in the United States and 50Hz in Europe.)
Current consumption while the machine is under full load.

**Current Rating** of the largest motor (the spindle motor for the machines analyzed in Chapter 3).

**Other variables** depending upon the machine related specifics.

![Figure 5-1: The specification plate on the actual machine provides basic information required to properly set up the machine with the correct power configuration.](image)

These parameters allow one to calculate the maximum power that the machine is able to consume, by multiplying the voltage feeding into the system by the current consumption as shown in *Equation 1.2*. For the Torq-Cut, which lists 230V as the voltage and 38A as the current consumption while the machine is under full load, the maximum power consumption would be 8740W. Looking at *Figure A-4*, we see that this number does not exactly match the 6990W measured, but it is close (the power consumption calculated has a 25.0% difference from the measured power consumption). *Table 5.1* shows each machine's calculated maximum power consumption and measured maximum power consumption. These results show that while not equal, the results to coincide.
Table 5.1: Calculated maximum power consumption using the specification plates on the machines compared to the experimental maximum power consumption measured in Chapter 3, show that while the two don’t match perfectly, they do correlate to each other.

These results are only significant for finding the maximum power that the machine could consume. Under normal circumstances, the power consumption will be less because the machining done will not push the machine to its maximum load. The specification plates do not show how much power goes into running the machines versus how much power is used to do the machining. Instead, they can only be used to find the maximum power that the machine is capable of consuming.

5.2 Maximum Power of Machining

By knowing the maximum amount of power that the machines in the Laboratory for Manufacturing and Productivity can consume, it is next desirable to estimate the power that goes into keeping the machine on (the constant amount of power used when idling) and the power that goes into machining the part. The power that goes into machining the part can be estimated by determining the theoretical amount of power needed to perform the cut. If the machine is running under maximum load, as it would be when the maximum amount of power was being used, then the cut being performed would represent the largest cut able to be performed on that machine.
If one could determine the largest cut that the machine can perform, and subtract that from the maximum amount of energy that the machine can use, one could get a proper estimate of the constant idle power.

\[ P_{total, \text{max}} = P_{idle} + P_{\text{machining, max}} \quad (5.1) \]

\[ P_{idle} = P_{total, \text{max}} - P_{\text{machining, max}} \quad (5.2) \]

By having performed experimental tests on the machines, we have the benefit of knowing the most power consuming cut able to be performed on the machines, and thus it is relatively easy to determine an estimate of the idle power, \( P_{\text{idle}} \). We simply take the value of \( P_{\text{machining, max}} \) from Table 5.1 and the largest power consumption used in the experimentation (which can be seen in Chapter 3 or in Appendix A), and plug these into Equation 5.2 above.

If, however, the machines are not accessible for experimentation, then determining the maximum power of machining becomes more difficult. However, because the machines rely on a single spindle motor to perform the machining, the power that the spindle motor is able to output (its rated maximum power) will be the maximum power of the machining process. Table 5.2 lists the spindle motor powers for each of the machines experimented upon in this project. A comparison with Table 5.1 shows the amount of power able to be output by the motors is lower than the maximum power consumption of the machines. The difference is an estimate of the idle power, defined in Equation 5.1.

Table 5.3 shows the calculated idle power consumption using Table 5.2 and Equation 5.2, and compares these results with the experimental results found in Chapter 3. The calculated idle power consumptions agree well with the experimental idle power consumptions, with the exception of the DaeWoo. The reason for this discrepancy is that the DaeWoo has an extremely large rated power, capable of over 33kW, whereas its motor can only deliver 11kW. With other machines, the rating is only slightly higher than the power of the spindle motor. This discrepancy shows one of the fundamental assumptions regarding this form of power estimation: the maximum
<table>
<thead>
<tr>
<th>Machine</th>
<th>Maximum Rated Power of the Motors (W)</th>
<th>Calculated Maximum Power Consumption (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engel 30</td>
<td>7640</td>
<td>11040</td>
</tr>
<tr>
<td>Bridgeport Milling Machines (both)</td>
<td>1490</td>
<td>2110</td>
</tr>
<tr>
<td>Bridgeport Torq-Cut TC3</td>
<td>7080</td>
<td>8740</td>
</tr>
<tr>
<td>Cincinnati Milacron 7VC</td>
<td>7640</td>
<td>12000</td>
</tr>
<tr>
<td>DaeWoo</td>
<td>11190</td>
<td>33000</td>
</tr>
<tr>
<td>Puma 8HC-3A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Maximum Rated Power of the Spindle Motors for each machine as compared to the maximum power consumption of the machine.

The power rating of a machine is attainable by putting the machine in the "on" position (which represents the idle power) and having the spindle motor work at 100% capacity (which represents the power going into machining). If this is not the case, as in with the lathe, then this form of power estimation does not work.

The next figures (Figure 5-2, Figure 5-3, Figure 5-4, Figure 5-5, and Figure 5-6) show graphically what is shown in Table 5.2 and Table 5.3 – the relationship between the estimations of power consumption versus the actual power consumption. Using the methods above, it is feasible to determine a rough estimate of the power consumption of the machines, both while idling and while machining.

In order to determine roughly how much power is needed for a certain part without making any physical measurements on the machine, one must first determine the maximum power of the machine and the power of the motors involved with the production of the part. With this, one can find an estimate of the idle power consumption of the machine. Next, by knowing the power needed to make the cut (e.g. in the case of the milling machine, $K_p$ of the part, the feed rate, diameter of cut, and depth), one can determine the amount of power that the machine will use while producing the part. This information, while not exact, is a useful first step in the determination of the part production's "cost" in power.
Table 5.3: Maximum Rated Power of the Spindle Motors for each machine as compared to the maximum power consumption of the machine.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Calculated Idle Power Consumption (W)</th>
<th>Experimental Idle Power Consumption (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engel 30</td>
<td>3400</td>
<td>3850</td>
</tr>
<tr>
<td>Bridgeport Milling</td>
<td>620</td>
<td>670</td>
</tr>
<tr>
<td>Machine #1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridgeport Milling</td>
<td>620</td>
<td>720</td>
</tr>
<tr>
<td>Machine #2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridgeport Torq-Cut TC3</td>
<td>1660</td>
<td>920</td>
</tr>
<tr>
<td>Cincinnati</td>
<td>4360</td>
<td>3360</td>
</tr>
<tr>
<td>Milacron 7VC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DaeWoo</td>
<td>21810</td>
<td>1770</td>
</tr>
<tr>
<td>Puma 8HC-3A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-2: A comparison of the power consumption estimation of the Engel 30 and the experimental power consumption.
Figure 5-3: A comparison of the power consumption estimation of the two Bridgeport manual milling machines and the experimental power consumptions.

Figure 5-4: A comparison of the power consumption estimation of the Bridgeport Torq-Cut Automated Milling Machine and the experimental power consumption.
Figure 5-5: A comparison of the power consumption estimation of the Cincinnati Milacron 7VC and the experimental power consumption.

Figure 5-6: A comparison of the power consumption estimation of the DaeWoo Puma 8HC-3A and the experimental power consumption. The estimation is quite different from the experimental results obtained.
Appendix A

Power Consumption Charts

The following charts detail the power consumption of the machines in the Laboratory for Manufacturing and Productivity. Each machine's power consumption is divided into processes required for startup – power that is used even when the machine is not producing a part – and processes during the run time of the part, both fixed and variable. The chart is further subdivided into the individual processes and the power consumption required for each individual process.
A.1 Engel 30 Injection-Molding Machine

Figure A-1: The power consumption of the Engel 30 Injection-Molding Machine graphically represented.
A.2 Bridgeport Manual Milling Machines

Figure A-2: The power consumption of the Bridgeport Manual Milling Machine graphically represented
Figure A-3: The power consumption of the second Bridgeport Manual Milling Machine. It is very similar to the previous chart.
### A.3 Bridgeport Torq-Cut TC3 Automated Milling Machine

![Diagram of power consumption breakdown](image)

**Figure A-4:** The power consumption of the Bridgeport Torq-Cut Automated Milling Machine represented graphically.

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carousel</td>
<td>0.4%</td>
<td>90</td>
</tr>
<tr>
<td>Spindle</td>
<td>9.9%</td>
<td>690</td>
</tr>
<tr>
<td>Tool Change</td>
<td>3.3%</td>
<td>230</td>
</tr>
<tr>
<td>Jog (x/y/z)</td>
<td>6.6%</td>
<td>460</td>
</tr>
<tr>
<td>Unloaded Motors</td>
<td>2.0%</td>
<td>140</td>
</tr>
<tr>
<td>Spindle Key</td>
<td>2.0%</td>
<td>140</td>
</tr>
<tr>
<td>Coolant Pump</td>
<td>2.0%</td>
<td>140</td>
</tr>
<tr>
<td>Servos</td>
<td>1.3%</td>
<td>90</td>
</tr>
<tr>
<td>Computer and Fans</td>
<td>5.9%</td>
<td>410</td>
</tr>
</tbody>
</table>

**Material Removal Rate:** 12.04 cubic cm/sec

**Variable Machining (65.8%) [6600 W]**

**Constant Run Time Operations (20.2%) [1470 W]**

**Constant Startup Process (13.2%) [920 W]**

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A.4  Cincinnati Milacron 7VC Automated Milling Machine

Figure A-5: The power consumption of the Cincinnati Milacron Automated Milling Machine represented graphically.
Figure A-6: The power consumption of the Daewoo Puma Automated Lathe Machine represented graphically.
Appendix B

G-Code Used to Produce Variable Loads on the Machines

In order to produce variable loads on the automated milling machines and automated lathe machines, it was necessary to create G-Code – the interpreted language used by the machines – to create cuts at certain depths. These codes were created using Mastercam software. The cuts were made on aluminum blocks that were 4.00in wide and 3.75in long. The blocks varied in depth, but were at least 0.50in deep, to accommodate the cutting passes made by the milling machines. The milling machines used a 3.15in diameter 3-flute cutting piece, in order to maximize the load that the machine experienced while cutting, allowing a greater range of measurements to be taken. Also, the feed rates on the machines were both set at 70 in/min.

B.1 Automated Milling Machine

The code shown below made four passes on the aluminum block. The first pass, shown on line 4 (the line beginning N4...), made a cut 0.075in deep. The second pass, shown on line 8 (N8), made another cut 0.075in deep. The third pass, shown on line 12 (N12), made a cut 0.150in deep. The final pass, shown on line 16 (N16), made a cut 0.200in deep.
N1G0G40G70G90T12M6
N2X5.35Y-2.S2000
N3Z.1M13
N4G1Z-.075F5.
N5X-1.6F70.
N6G40G0Z.1
N7X5.35
N8G1Z-.15F5.
N9X-1.6F70.
N10G40G0Z.1
N11X5.35
N12G1Z-.3F5.
N13X-1.6F70.
N14G40G0Z.1
N15X5.35
N16G1Z-.5F5.
N17X-1.6F70.
N14G40G0Z.1
N19M2
%

72
B.2 Automated Lathe Machine

The code shown below made three passes on the aluminum block. The first pass, at line \textit{N8}, made a cut 0.050\textit{in} deep. The second pass, at line \textit{N39}, made a cut 0.100\textit{in} deep. The third pass, at line \textit{N65}, made a cut 0.150\textit{in} deep.

```
% 00000(T)
N1G20
(TOOL-1 OFFSET-1)
(FACE/TURN WITH RADIUS INSERT-55 DEV. DIAMOND)
N2G0X14.Z5.
N3G0T0101
N4G97S730M3
N5G0X5.1414Z.0207M8
N6G50S4000
N7G96S600
N8G99G1X3.Z-.05F.03
N9X0.
N10G0X.1414Z.0207
N11M9
N12M5
N13G0X14.Z5.T0100
N32M01
(TOOL-1 OFFSET-1)
(FACE/TURN WITH RADIUS INSERT-55 DEG. DIAMOND)
N33G0X14.Z5.
N34G0T0101
G35G97S730M3
N36G0X5.1414Z-.0793M8
N37G50S4000
N38G96S600
N39G1X3.Z-.15F.03
N40X0
N41G0X.1414Z-.0793
N42M9
N43M5
N44G0X14.Z5.T0100
N45M01
(TOOL-1 OFFSET-1)
(FACE/TURN WITH RADIUS INSERT-55 DEG. DIAMOND)
```
N60 G0 T0101
G61 G97 S730 M3
N62 G0 X5.1414 Z-.2293 M8
N63 G50 S4000
N64 G96 S600
N65 G1 X3 Z-0.3F.03
N66 X0
N67 G0 X.1414 Z-.2293
N68 M9
N69 M5
N70 G0 X14 Z5 T0100
N71 M30
%

Bibliography

*LAB741 - Measure Power In 3-Phase Systems.* LeCroy Corporation,  


[3] Chuck Bennett. *Ammeter HowTo.* University of North Carolina at Asheville,  


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