

An Environmental Impact Analysis of Grinding

By

Beth Baniszewski

Submitted to the Department of Mechanical
Engineering in Partial Fulfillment of
the Requirements for the Degree of

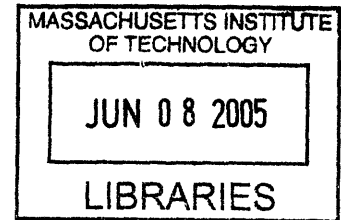
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Abstract

This thesis was intended to investigate the environmental impact of grinding in the United States manufacturing industry. Grinding is an ideal method for producing parts with a fine surface finish and high dimensional accuracy and for shaping hard or brittle workpieces. There are a wide variety of different types of grinding machines, each with different applications and slightly different energy requirements. Workpieces are generally flooded with a stream of coolant while being ground or placed in a spray of coolant mist. Coolant recycling systems are used to filter ground off chips out of coolant and to remove foreign oils and bacteria which pose health hazards. Oil mist collectors both clean mist coolant and prevent the toxic coolant from being inhaled by machinists. In total, 63×10^{15} joules of energy are consumed per year by grinding in manufacturing, 57% of which is directly used in material removal. A total of 1.5×10^{10} pounds of scrap chips, spent grinding wheels, and used filters are produced each year as a result of grinding, over 99% of that being scrap chips. About 2.3 million gallons of fluids per year of grinding fluids are incinerated. Grinding creates a significant environmental footprint, creating a need for methods to reduce energy use in grinding and for ways to recycle solid waste that would otherwise be sent to landfills or incinerated.

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Introduction

The most common method for producing parts which require a fine surface finish or high dimensionally accuracy is abrasive machining, also known as grinding. Grinding not only allows parts to be produced with fine surface finish and dimensional accuracy requirements, but it also very effective for handling hard or brittle work piece materials. (Kalpakjian, 2001) Parts such as ball and roller bearings, cams, gears, valves, cylinders, pistons, cutting tools and dies, and precision components for instrumentation are typically produced by grinding. Grinding is also used to finish hard or heat treated parts, to shape ceramics and glasses, and to remove unwanted weld beads and spatter.

There are several varieties of grinding -- surface grinding, cylindrical grinding, centerless grinding, creep feed grinding -- each of which is used for different applications and which requires slightly different inputs in terms of energy, grinding wheels, and coolant. Although less than a thousandth of an inch of material may be ground off any given surface of a part, so the amount of solid waste created compared to the quantity of parts made will be small, waste is also created in the form of spent grinding wheels and used grinding fluids. This thesis will examine the amount of waste produced by the grinding industry and its means of disposal. Furthermore, the energy needed to run grinding machines and associated machines such as coolant recycling centrifuges or air cleaning mist collectors is not insignificant and will be examined. The energy required to machine, cast, or otherwise create the rough parts sent into grinders has been the subject of other studies (Dahmus, 2004) (Dalquist, 2004) and will not be included in this analysis.

Overview of Grinding in Industry

The number of grinding machines in use in industries in the United States varies widely by type. The most widely used grinders are flat surface grinding machines. Numerically controlled grinding machines are also less common than non-numerically controlled grinding machines, since grinding machines have a long life span and many old, non-numerically controlled grinding machines have not been replaced with updated technology. Still, numerically controlled grinders do continue to make up a larger and larger percentage of grinding machines in use. These machines are able to be positioned faster and therefore spend less of their up time idling, making them more efficient, but the computer systems do cause some increase in the power requirement for operating the machines. Furthermore, creep feed grinding, which produces nearly one hundred times as much solid waste and requires nearly one hundred times as much energy than standard grinding, has grown in use, though it still remains a minor percentage total grinding in the United States.

According to the Association for Manufacturing Technology's most recent inventory of machine tool imports, exports, and domestic usage, (AMT, 1997) nearly one third off all imported grinders are flat surface grinding machines. Finishing machines are the next largest import, followed by tool or cutter grinding machines. Cylindrical grinding machines and honing or lapping machines made up only a small percentage of imports. Creep feed grinder imports were not significant enough to be listed in their own category, rather they were classified under "other grinding machines."

The summary of grinding machine exports` showed a very different distribution, as finishing machines and honing or lapping machines each made up nearly a third of total grinding machine exports, while the other flat surface, cylindrical, tool or cutter, and other grinding machines each constituted only a small portion of the overall total. Still, this thesis is intended to

discuss energy use and waste production by grinding operations performed in the United States, so import figures will reflect the number of grinding machines in use in the United States more accurately than export figures. Furthermore, the summary of grinding and polishing machine shipments within the United States for machines of unit value \$3,025 and over again shows surface grinding machines as the most abundant, with tool and cutter machines and honing and lapping machines the next most common.

Combining the number of grinding machines imported and the number shipped within the U.S. during 1995, it appears that for new grinder acquisitions that year, 33% were surface grinding machines, 21% were polishing or finishing machines, 11% were tool or cutter machines, 8% were honing or lapping machines, 7% were cylindrical grinders, and 20% were other varieties of grinding machine. In total, 16,060 new grinding units were acquired by US. grinding operations in 1995. These new machines constituted 6% of the 261,813 total grinding units reported to the inventory.

Of imported grinding machines, 15% are numerically controlled, though the proportion of numerically controlled grinding machines varies widely by category, with 30% of honing or lapping machines being numerically controlled, but only 9% for polishing and finishing machines. It can be safely assumed that numerically controlled machines make up an even smaller percentage of older grinders.

It is somewhat difficult to determine how quickly the total percentage of numerically controlled machines in use in the United States is expanding, because the Association for Manufacturing Technology machine inventory published in 1997 contradicts the industry trends found in American Machinist's 14th Inventory of Metalworking Equipment (American Machinist, 1989). The AMT inventory was an expanded document including the 15th American Machinist Inventory, so similar survey methods would have been used for both studies. Yet, the

14th inventory indicated that, on average, operational grinding machines in U.S. manufacturing facilities were getting younger, while the 15th Inventory shows a smaller proportion of new machines than the 14th. In the 14th inventory in 1989, 3% of reported grinding machines in use were numerically controlled, but of machines less than five years old, 8% were reported as numerically controlled. Furthermore, the 14th inventory reported that 14.5% of grinding machines in use were less than five years old, while the 15th inventory reports that only 12.1% of grinding machines in use were less than six years old. Though both the 13th and 14th inventories reported more new machines in use than ever before, the 1990s saw a trend back towards keeping old machines around, despite the fact that economic growth in the mid 1990s was at least as strong as growth in the 1980s (Miller, 2004). It is possible that the drive towards newer machines indicated in the 13th and 14th inventories was a response to new developments in grinder technology, and now the market has been filled with the majority of the upgrades it requires. Even though a larger percentage of new grinders are numerically controlled than ever before, fewer new grinders are required, since numerical control is no longer a new technology.

The apparent increase in average grinder age between the 14th and 15th inventories could also be a result of changes in the size of production plants. Although the 14th inventory reported that more machine tools were being used in small facilities than ever before, the 15th inventory shows a switch back towards larger plants. In the 14th report, 24% of grinding equipment was found in plants with fewer than 20 workers, 44% in plants with 20-99 workers, 22% in plants with 100-499 workers, and 10% in plants with more than 500 workers. The 15th inventory showed a significant decrease in the smallest category, and an increase in the second largest category, such that only 19% of grinding machines were found in plants with fewer than 20 workers, 45% in plants with 20-99 workers, 26% in plants with 100-499 workers, and 10% in plants with more than 500 workers. This trend towards larger facilities will mean that each

machine is in use a greater percentage of the time, and that coolant recycling systems and mist collecting systems are in greater demand.

Though relegated to the “other grinding machines” category in the above inventories, creep feed grinders are growing in use. Though mostly used for machining aerospace engine components such as turbine blades, creep feed grinding is also used to manufacture automotive engine and drive train components, parts for the military and tiny medical parts (Gordon, 2004). Creep feed grinders are often used to create deep slots or complicated profiles (Albert, 200x). As a process involving fewer steps to create a complex part than conventional machining and grinding, particularly on hardened workpieces, creep feed grinding is growing as a method of high speed production. The expense of the machines prevents their spread to a degree, but the savings created by replacing several machines with one is a draw for companies with adequate capital. Creep feed grinders use spindles with motors anywhere from 6 to 225 kilowatts, while spindles on surface and cylindrical grinders typically have 1 to 5 kilowatt motors. Powerful “universal” grinders, which can be used for creep feed and conventional grinding are also increasing in popularity. They typically contain 7.5 kilowatt spindle motors. With 20% of grinding machines in the United States falling under the category of “other”, and creep feed and universal grinders making up a significant portion of this category, they are certainly not to be excluded from a discussion of grinding machines, particularly given their high energy requirements and large amount of scrap produced.

Though the most abundant grinders presently in use are manually controlled surface grinding or polishing and finishing machines, numerically controlled machines have become a fixture in industry and machines like creep feed grinders may become more prevalent as production facilities scale back up.

Detailed Description of Grinding Machines

The main abrasive machining operations are surface grinding, cylindrical grinding, internal grinding, centerless grinding, creep-feed grinding, honing, and lapping. A number of other, specialty grinding machines are also used in manufacturing. Steels and cast iron are most commonly ground, but aluminum, brass, bronze, copper, titanium, nickel alloys, nylon, carbides, and ceramics are also ground. Grinding is one of the few effective ways of shaping hard, brittle materials like ceramics while they are cold.

Surface grinding is the most common abrasive machining operation, and it involves grinding flat surfaces. Work pieces are held to the work table of the grinder via a magnetic chuck, or if the work piece is not magnetic, it is held by vises, vacuum chucks, double sided adhesive tape, or special fixtures (Kalpakjian, 2001). A grinding wheel, mounted on the horizontal spindle of the grinder, rotating at 1500 to 3000 m/min, is used to remove material. A typical horizontal spindle surface grinder is shown in Figure 1.

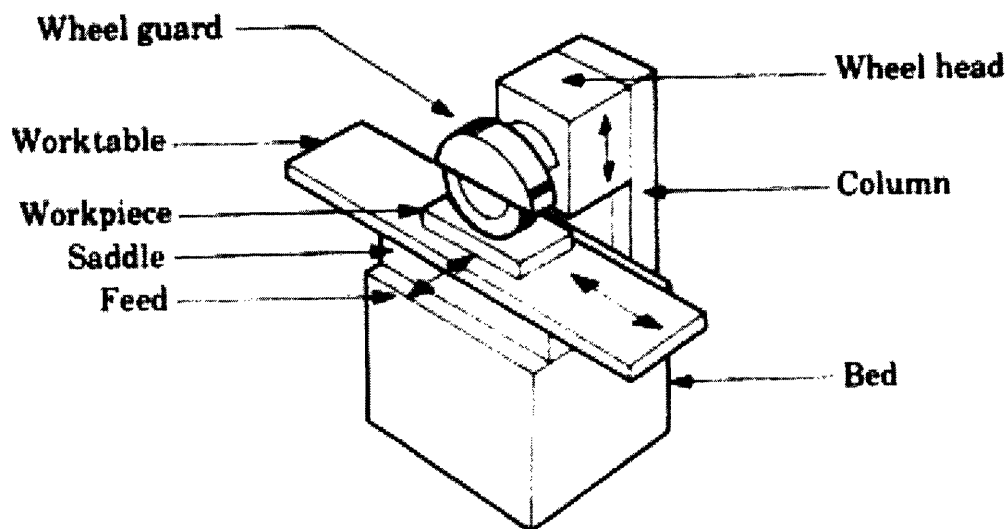


Figure 1: Illustration of a typical surface grinder. (Kalpakjian, 2001)

Three typical surface grinding operations are depicted in Figure 2. In transverse grinding, the work table reciprocates longitudinally, bringing part of the work piece in front of the grinding wheel, then moves laterally to feed the part under the wheel. It then reciprocates again to bring a new section of the part in range of the wheel until the entire surface has been ground. In plunge grinding, the grinding wheel is moved radially into the work piece, grinding a groove into the surface. Grinders with vertical spindles can allow numerous pieces such as ball bearings to be ground in one setup by bringing the face of the grinding wheel down flat against a special rotary fixture.

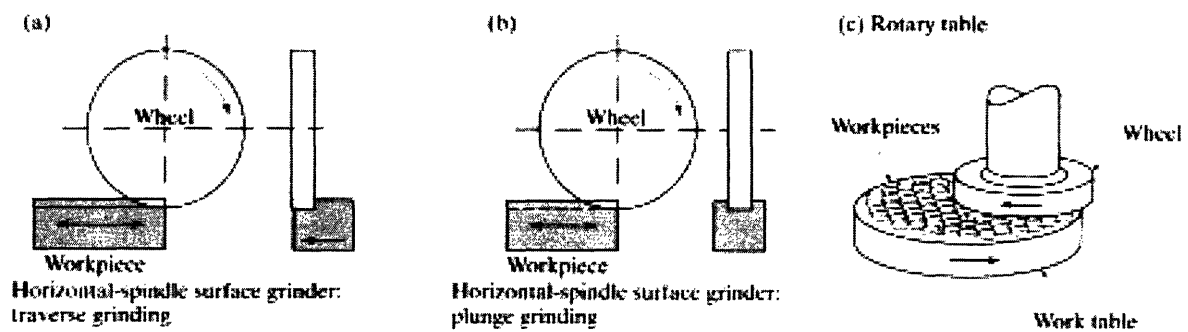


Figure 2: Illustrations of surface grinding operations. a) Transverse grinding with a horizontal spindle. b) Plunge grinding with a horizontal spindle c) Rotary table grinding with a vertical spindle. (Kalpakjian, 2001)

Cylindrical grinding is used to grind cylindrical surfaces. Cylindrical grinding can either be center-type or centerless. External center-type grinding is often used to make crankshaft bearings, spindles, pins, and other cylindrical parts. The workpiece is either held between centers, placed in a chuck, or mounted on a faceplate in the headstock of the grinder. Separate motors rotate the grinding wheel and workpiece around parallel axes, and the workpiece reciprocates along its axis until its entire length has been ground. In grinding operations where the

workpiece is very large, the grinding wheel may reciprocate instead. Various cylindrical grinding operations are shown in Figure 3.

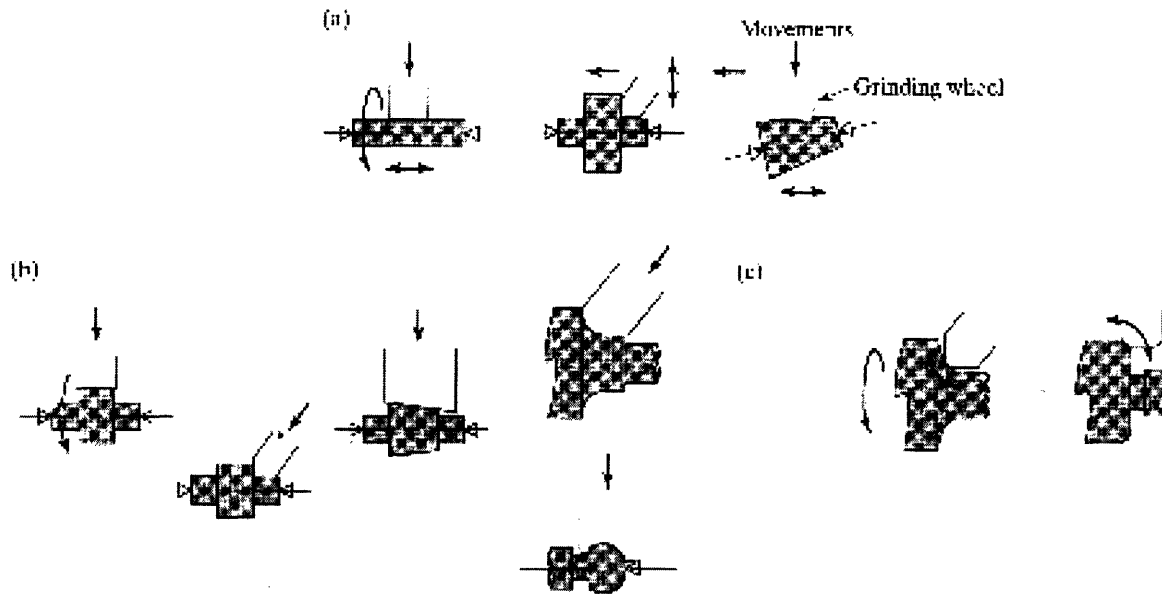


Figure 3: Various external cylindrical grinding operations. a) Traverse grinding. b) Plunge grinding. c). profile grinding. (Kalpakjian, 2001)

In numerically controlled machines, computer controls allow the grinding process to be automated, and they also allow noncylindrical parts to be created on cylindrical grinders. The part rotation and distance between the centers of the part and the grinding wheel may be varied precisely via computer in such a way as to grind cams and similar parts. Such a process is illustrated in Figure 4.

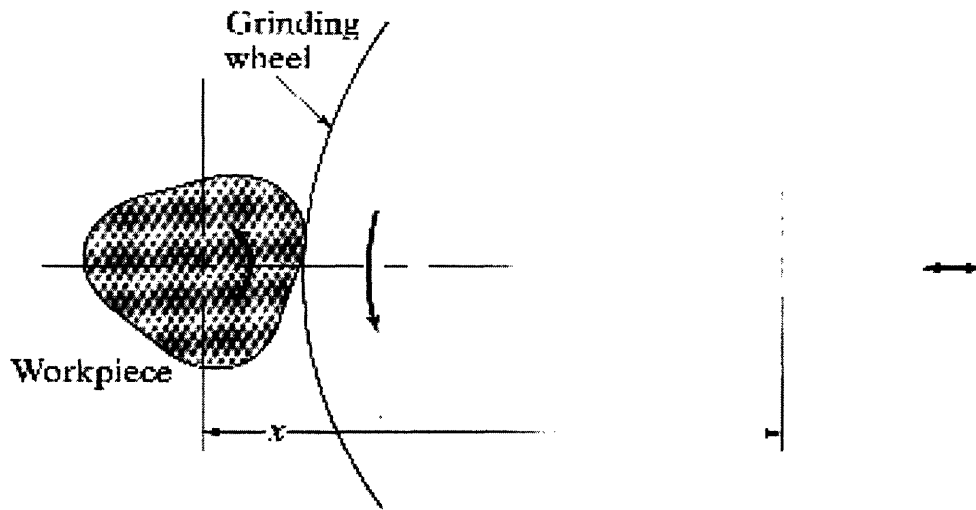


Figure 4: Schematic of grinding a noncylindrical part on a computer controlled cylindrical grinder. The part rotation and the distance between centers, x , is varied and synchronized to produce a specific workpiece shape. (Kalpakjian, 2001)

Grinding wheels can be shaped, also known as “dressed”, in order to grind particular shapes into parts. Highly accurate thread grinding is done through cylindrical grinding of with a wheel dressed to match the profile of the threads. Modern computer controlled grinding machines are often equipped with automatic dressing features which continually shape the grinding wheel as the machine is operating so that the wheel does not lose its required contours while wearing against the workpiece. Grinding a shaped workpiece with a dressed wheel is shown in Figure 5.

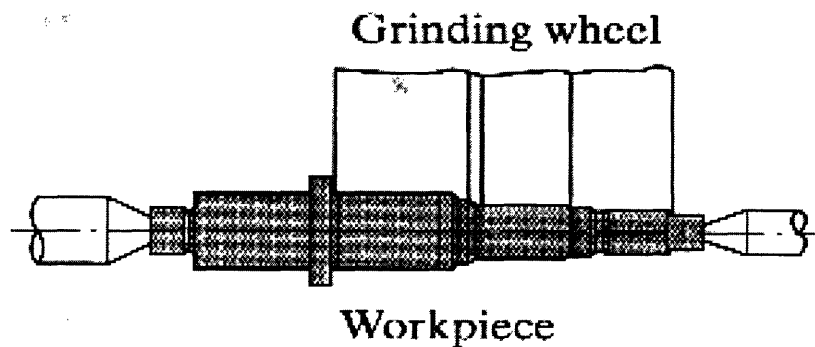


Figure 5: Plunge grinding on a cylindrical grinder with a dressed wheel to produce a specialized

shape. (Kalpakjian, 2001)

Internal center-type grinding is used to grind the inner diameters of parts such as bushings and bearings. In internal grinding, a small grinding wheel, possibly dressed with a particular profile, is positioned inside the diameter to be ground and rotated at very high speeds of over 30,000 rpm, as depicted in Figure 6.

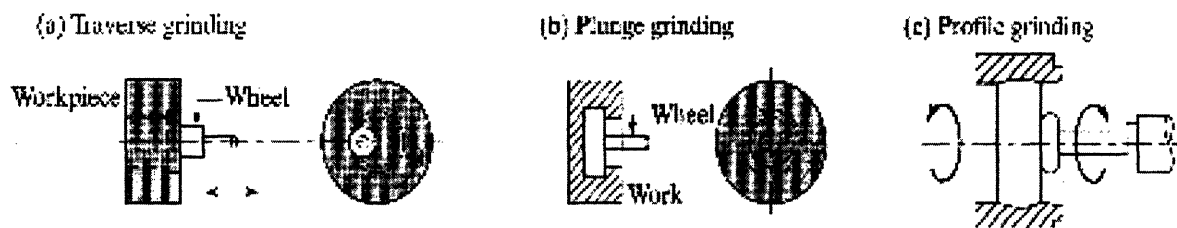


Figure 6: Internal grinding operations. (Kalpakjian, 2001)

Centerless cylindrical grinding does not require workpieces to be supported by centers of chucks, and it therefore allows continuous grinding of cylindrical surfaces on successive parts in a high-production process. Rather than being held between centers, parts in centerless grinding are supported beneath by a blade. They are ground by a large wheel to one side and supported by a rubber coated, slower spinning regulating wheel on the other. External centerless grinding is depicted in Figure 7. Parts typically produced in this way include roller bearings, cam shafts, engine valves, and piston pins. Parts as small as 0.1 mm in diameter can be ground in this way. Tapered or threaded pieces may be ground by centerless grinding with properly dressed wheels. Internal centerless grinding may also be conducted in order to grind the insides of sleeve-shaped parts and rings. In this process, the workpiece is supported by three rolls and internally ground.

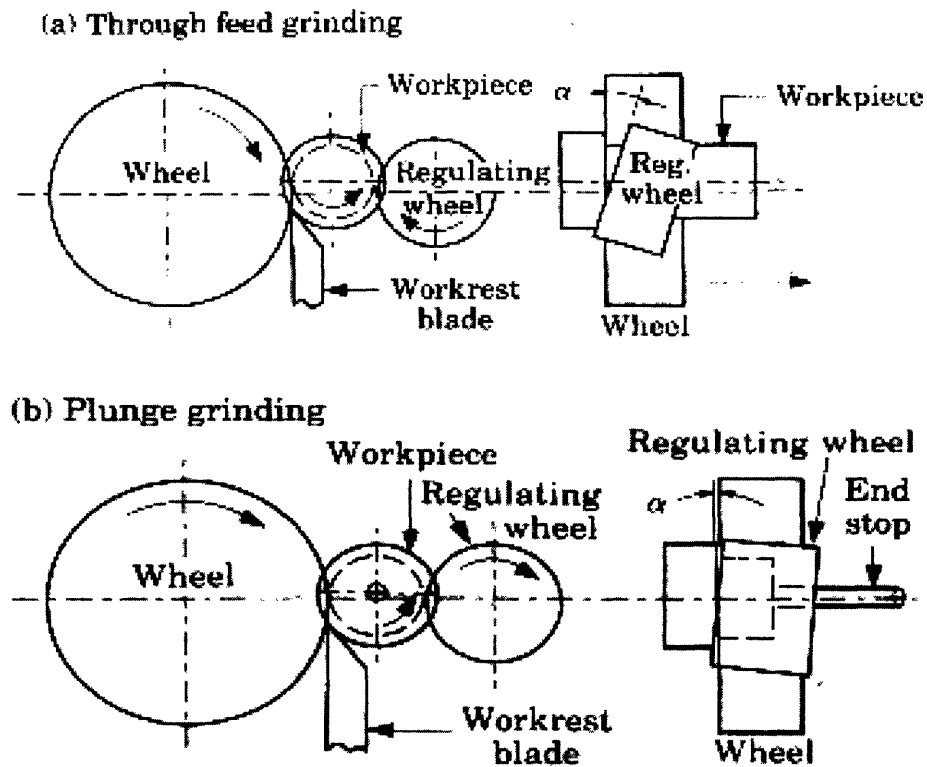


Figure 7: External centerless grinding operations. (Kalpakjian, 2001)

Creep feed grinding was developed in the 1950s as a high precision method for large scale material removal. Unlike other types of grinding where only small amounts of material are removed, cut depths in creep feed grinding can be up to 6 mm. As a result, workpiece speeds are slower than in traditional grinding. Rough castings and forgings can be ground to completion in this way without any prior machining. Creep feed grinding machines are similar in design to surface and cylindrical grinders, but with more powerful motors, higher stiffness, high damping capacity, variable speeds, and a larger capacity for grinding fluids. Creep feed grinding wheels may be continually dressed with a diamond roll.

Honing is a finishing operation most often used to give holes an extra fine surface finish, though it is also used to finish external cylindrical and flat surfaces, and to remove sharp edges on inserts and cutting tools. A honing tool consists of a spindle upon which aluminum-

oxide or silicon-carbide abrasives called stones are mounted, as illustrated in Figure 8. The spindle rotates in a hole, applying radial force while reciprocating axially. The stones are adjustable for honing differently sized holes. In external cylindrical and centerless honing, a stone reciprocates while the workpiece is rotated, as shown in Figure 9.

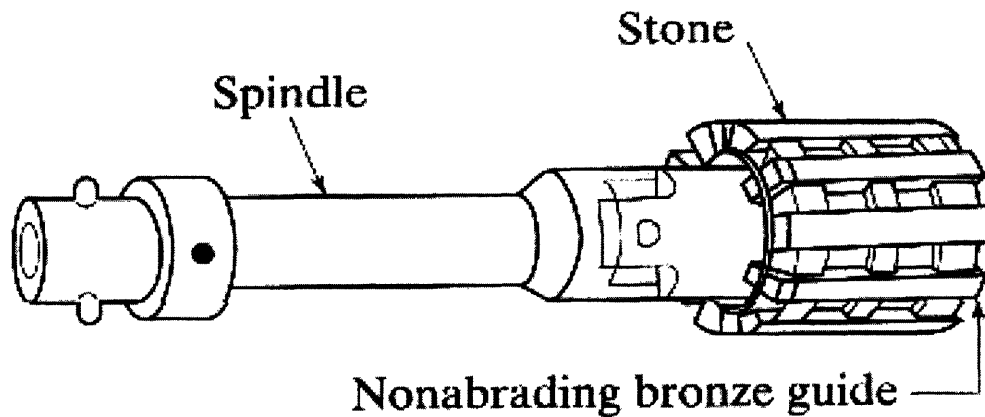


Figure 8: Schematic of a honing tool used to improve the surface finish of holes. (Kalpakjian, 2001)

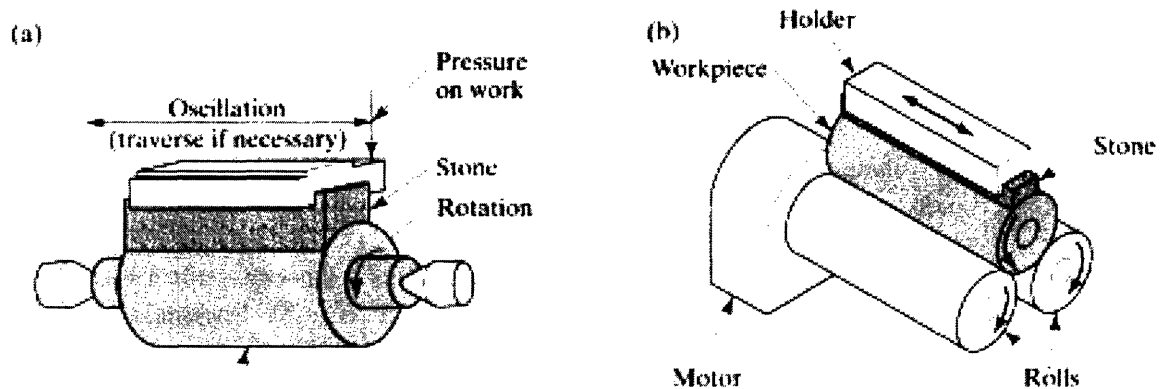


Figure 9: Illustrations of a) cylindrical and b) centerless honing. (Kalpakjian, 2001)

Lapping is another finishing operation used to produce extra fine surface finishes, which can be as smooth as 0.025 to 0.1 micrometers. The workpiece is held between an upper and

lower lap, shaped fixtures made from cast iron, copper, leather, or cloth. Abrasive particles are embedded in the lap or carried in through a slurry. The lap pieces are pressed together at pressures of up to 140 kPa and rotate in opposite directions around the fixed workpiece. Specially shaped laps can be used to finish spheres and other irregular shapes.

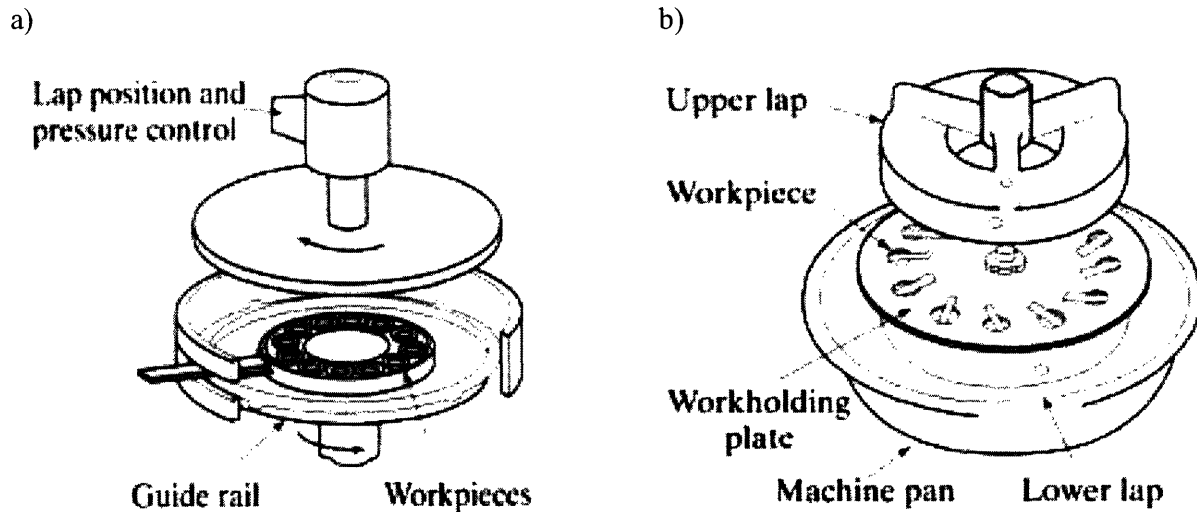


Figure 10: Production lapping on a) flat and b) cylindrical surfaces. (Kalpakjian, 2001)

Polishing is a fine scale surface finishing operation designed to leave a smooth, lustrous surface finish without the circular or crosshatched patterns that are often left by other abrasive machining processes. Polishing is usually used after these processes are completed to achieve the final finish. Disks or belts made of fabric, leather, or felt and coated with fine aluminum oxide or diamond powders are used to remove material on a fine scale and create frictional heat which is used to soften and smear the surface layers of the workpiece material, creating a shiny surface.

Other special purpose grinders are also used in manufacturing. Universal tool and cutter grinders are equipped with special work-holding devices which provide accurate positioning for grinding single point or multipoint tools and cutters, including drills. Tool post grinders are units

attached to the tool post of a lathe. Swing-frame grinders are large grinders used for grinding large castings in foundries. Bench grinders are usually equipped with both a coarse wheel for rough grinding and a fine wheel for finishing, mounted on opposite ends of one shaft. They are used for offhand grinding for various tools and small parts. Portable grinders can be used for grinding off weld beads or for cutting-off operations using abrasive disks. They are used on large or difficult to move parts and are driven pneumatically, electrically, or via a flexible shaft connected to a gasoline engine or electric motor.

In general, a grinding machine consists of a grinding wheel on a rotating spindle, and a table or chuck which feeds the workpiece past the grinding wheel. The exact configuration of the machine, feed rates, abrasive composition, coolant use, and power consumption vary with the type of grinder. Coolant use and power consumption will be discussed in a later section.

Detailed Description of Coolants and Coolant Recycling Systems

Grinding fluids improve the efficiency of grinding operations by reducing the wear on grinding wheels and by lowering power consumption. The fluids absorb heat created during grinding and reduce friction, improving the parts' surface finish and dimensional accuracy. grinding fluids also remove chips from the surface of the part being worked (Kalpakjian, 2001). Water-based emulsions are typically used for general grinding, while oils are most often used for thread grinding. The fluid is applied in a fast stream under pressure through nozzles, or applied as a mist to reach inaccessible areas and provide better visibility of the workpiece.

As grinding fluids remove heat from the part, they can increase in temperature significantly, particularly if they are water-based. Grinding fluids which drip off the part are collected and circulated through refrigerating systems, allowing them to continue to cool the part when they are reapplied. After machining, cutting fluids must be removed from parts, either mechanically or via solvents. Water based emulsions are commonly used for grinding fluids since they are easy to remove.

In flood cooling, a stream of coolant is applied at a rate of about 10 liters (2.64 gallons) per minute, at pressures anywhere from 700 kPa to 14,000 kPa (Kalpakjian, 2001). Mist cooling is usually applied at air pressures of 70 kPa to 600 kPa. Since mist cooling deposits less coolant at once, it is not as useful in situations requiring a large cooling capacity, but it usually works well for grinding since only small amounts of material are removed at a time. Mist cooling requires venting in order to prevent machine operators from inhaling toxic fluid particles. Fumes from cutting fluids can cause respiratory problems and severe skin irritation, so many factories make use of mist collectors to reduce risk to their machinists. Mist collectors will be described in the next section.

As grinding fluids are recirculated through a grinder, they slowly accumulate tiny bits of

metal chips. If a grinder is left standing unused long enough for the chips to settle, many of the chips may be scooped out. This method of cleaning the fluid does not remove all the impurities, and eventually the grinding fluid will need to be more thoroughly cleaned or replaced.

In order to cut down on costs due to buying new grinding fluid and paying for safe disposal of old fluids, high production grinding facilities recycle their own grinding fluid or pay to have it recycled. Numerous machines exist which cleanse high volumes of grinding fluids via centrifuging and filtering, extending fluid life almost indefinitely (Hawks, 1998).

The Xybex series of coolant recycling systems, made by Master chemical Corporation, allow closed-loop coolant recycling inside an operating production plant. The first component of the Portable Xybex Coolant Recycling System, shown in Figure 11, is a sump pump, which pumps dirty coolant, chips, and fines through a filter to remove solids (Master Chemical Corporation, 2002). Once the fluid has been filtered, the sump pump returns it to the machine tool for reuse. A side stream of filtered fluid can be purified of tramp oils and other extraneous fluids by the Xybex centrifuge while the machine tool is running. Tramp oils are extraneous oils, usually from machine lubrication, which become mixed in with the coolant (Garrett, 1996). They tend to float on top of the coolant where they produce harmful bacteria. If tramp oils are not filtered out, bactericides containing containing toxic agents such as chlorine, bromine, and formaldehyde must be added to grinding fluids to keep bacteria levels down. If tramp oils are present at the machining surface, smoke containing toxic heavy metals can result. Once tramp oils are centrifuged out, the Xybex system may then be moved to another machine.

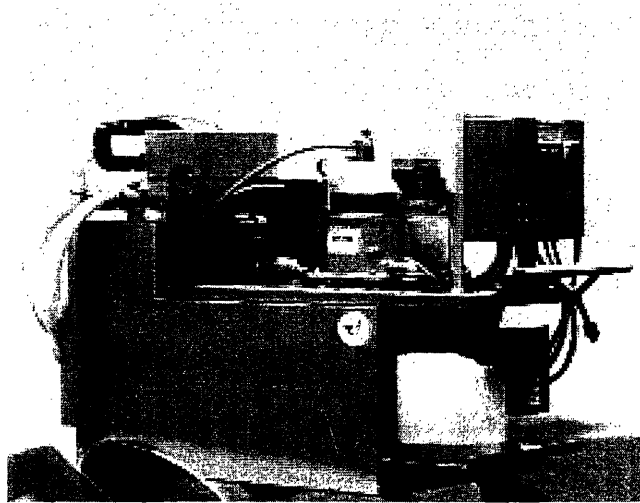


Figure 11: The Portable Xybex Coolant Recycling System (Master Chemical Corporation, 2002)

Sanborn Technologies' Patriot Recovery system combines high speed centrifugation with pasteurization to remove biological contaminants such as bacteria, mold, yeast, and fungi, in addition to solids and tramp oils (Sanborn Technologies, 2005). The heating due to pasteurization also lowers fluid viscosity to make the centrifuge more efficient and removes dissolved gasses like H₂S. The system can process up to two gallons of water based fluids per minute. The system is equipped with programmable microprocessors which allow it to pump, clean, and return fluids all while unattended.

Many higher volume coolant recycling machines are also in use. U.S. Centrifuge makes a wide variety of coolant recycling systems. The Duramatic A440 uses a 7.5 HP motor and can process up to 40 gallons per minute. U.S. Centrifuge's automatic centrifuges are self cleaning, so when the unit has reached its capacity for the amount of solids it can hold, the machine pauses its normal operations and solids are scraped out of the bowl down a sludge chute into a hopper placed below the unit (USC, 2005). This cleaning process takes three to five minutes. U.S. Centrifuge's largest coolant recycling machine is the CQ5 Decanter Centrifuge, which uses a 50 HP motor and can cleanup to 200 gallons of fluid per minute. For smaller manufacturing

operations, U.S. Centrifuge also offers a manually cleaned centrifuge which cleans 1 to 12 gallons of fluid per minute using a 2 HP motor. In general, the motor of a centrifuge will be about .3 HP per gallon per minute of fluid it can process.

Energy is expended in cleaning grinding fluids, but as a result, the volume of fluids which must be produced is dramatically reduced, and the clean fluids can even more effectively reduce friction and energy use in grinding machines.

Detailed Description of Mist Collectors

Oil mist collectors keep lubricating oils applied as mists from spreading through a production facility and causing respiratory problems for machinists. They also prevent oil mists from dispersing into the atmosphere. Mist collectors use a fan to pull mist through a series of filters to a drum where the oil is collected and can be reused (AER Control Systems, 2003). A hood or enclosure is placed above the machine which uses mist cooling. A hose connects an opening in the hood to the mist collector machine. A fan pulls air up through the hose and through a series of filters which remove solid particles from the fluid. The Troy Filters Stealth 1600 mist collector is shown in Figure 12.

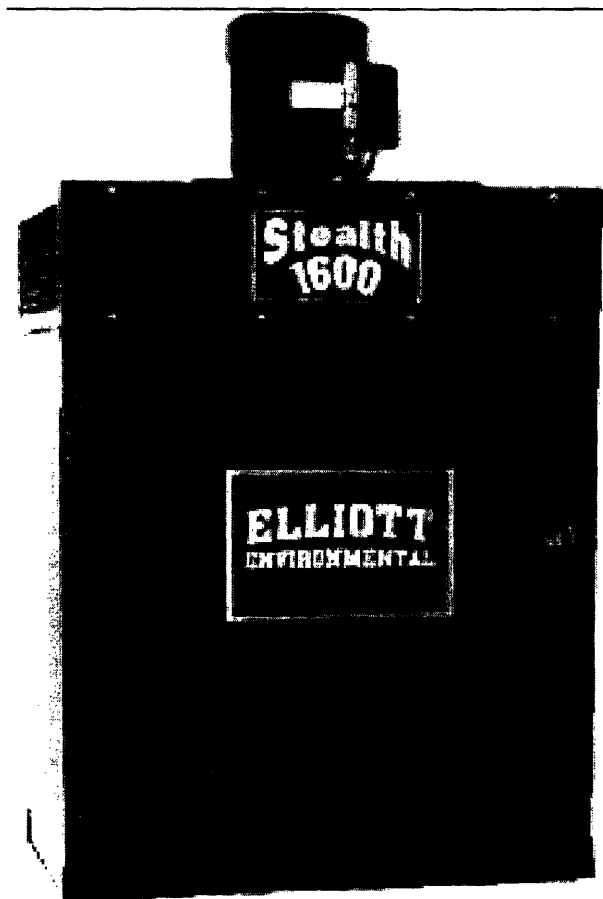


Figure 12: The Troy Filters Stealth 1600, a typical mist collector. (Troy Filters, Ltd., 2004)

Mist collectors tend to have a primary intake filter which catches most solid particles and one secondary intake filter. The primary filter is replaced anywhere from once a year to once a month, depending on the concentration of solid particle in the filtered mist. The secondary filter is not typically replaced. Grinding tends to generate a high concentration of dust, so not only is the primary filter replaced frequently, but an extra “prefilter” is typically installed and replaced regularly. Filters are thrown away when they have become too embedded with particles.

Once the oil mist has passed through the intake filters, the rotating blades inside the main drum of the collector act as a centrifuge to separate the oil particles from the air. The oil collected in the drum flows down a drain hose to be collected in a reservoir or it flows directly back into the unit which dispenses the coolant for the machine tool.

Once the oil particles are removed from the air, it flows through a final exhaust filter and back into the atmosphere. In situations where the filtered mist may be mixed with smoke, as sometimes occurs in grinding, a HEPA filter is placed on the exhaust end of the mist collector unit to prevent fine toxic smoke particles from passing back into the atmosphere with the exhaust stream of air.

Small mist collectors can process up to 900 standard cubic feet per minute of oil mist at 1.5 HP, while more heavy duty collectors can process up to 2400 cubic feet at 7.5 HP (Globalspec, 2005). Midsized mist collectors have about 5 HP motors. As mist collectors filter solid particles from the coolant, machines which use mist cooling do not require their coolant to be recycled regularly by the machines described in the the previous section, though such machines would still be valuable in removing tramp oils.

Energy Usage Measurements for the Okamoto ACC-8-20DX

In order to compare actual energy consumption by a grinding machine to the information listed on machine specification sheets, the current drawn by the Okamoto ACC-8-20DX, a standard surface grinding machine shown in Figure 13, was measured with a Yokogawa CL120 Clamp-on Tester, shown in Figure 14. The grinding machine was connected to 480 V three phase power. When the machine is switched on, power is used by the control panel. There are four systems which the control panel can be used to activate: the coolant pump, the grinding wheel spindle, a fan to suck away dust, and a hydraulic pump which is used to move the table on which the workpiece is held.

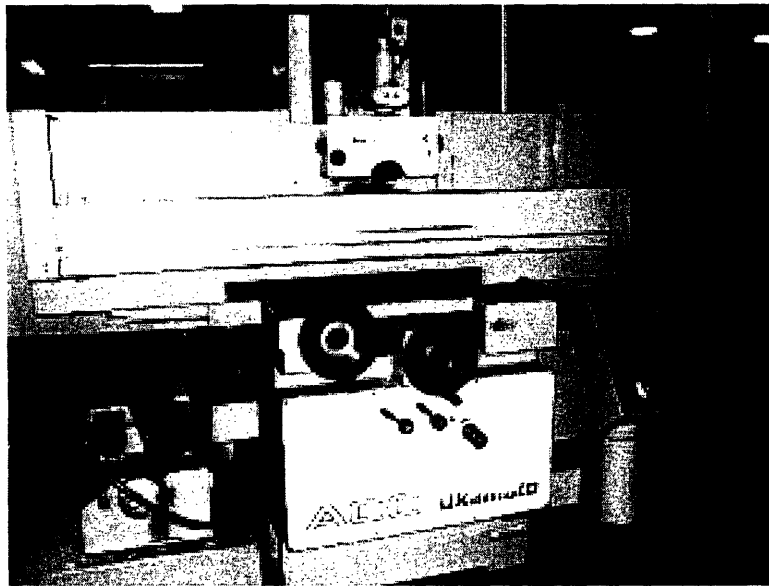


Figure 13: The Okamoto ACC-8-20DX surface grinder.

Current measurements were taken when only the control panel was powered, when each individual system was powered, and when the systems were powered in each possible combination. Line currents were measured in each of the three power wires, and power was

computed from the average line current. The control panel alone was calculated as using 47 watts of power. The coolant pump used an additional 27 watts, and the dust fan used 213 watts. Turning the grinding wheel on and allowing it to free rotate consumed another 302 watts. Activating the hydraulic pump, but not actually using it to move the worktable, drew another 224 watts. Thus, even when the machine was idle, simply having all systems powered required 813 watts of electricity.

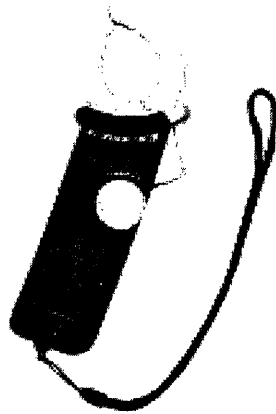


Figure 14: The Yokogawa CL120 Clamp-on Tester.

The current was also measured while only hydraulic pump was activated and the pump was moving the workpiece table. These measurements were compared to those taken while the hydraulic pump was activated but at rest, and it was determined that moving the table in order to position the workpiece required between 42 and 125 watts, depending on whether the table was moving longitudinally or laterally, and changing over the course of a stroke. For most of the stroke, about 80 watts were needed. So, if all systems of the grinder were powered and a piece was being positioned, 893 watts would be required.

The current drawn by the Okamoto ACC-8-20DX was measured while it ground a block of steel at a depth of 15 thousandths of an inch (0.381 mm) and at a depth of 10 thousandths of

an inch (0.254 mm). Comparing the power consumed while cutting to the power used while simply moving the table, cutting at a depth of 0.381 mm used about 60 additional watts, while cutting at a depth of 0.254 mm used between 105 and 255 watts, depending on the segment of the feed stroke. Clearly there was some source of error in the measurements, as the deeper cut should have required more energy. The workpiece ground did have a thin layer of rust coating its surface, so the 0.381 mm cut, which was executed first, would have been removing rust as well as steel, whereas the 0.254 mm cut, which was performed second, would have been removing mostly steel, therefore requiring more power.

Still, theoretical calculations for how much power should have been required to make the cuts show that the measurements are at about the expected magnitude. Given that the grinder was making a 9 (228.6 mm) inch stroke across a 1 inch (25.4 mm) segment of the workpiece every second, 16.6 cubic millimeters per second of material were being removed during the deeper cut, and 11 cubic millimeters per second during the second cut. The specific energy requirement for removing low carbon steel is between 14 and 68 W*s/mm³, depending on the steel (Kalpakjian, 2001), which means that the 0.381 mm cut should have used 232 to 1128 watts and the 0.254 mm cut should have used 155 to 752 watts. The measured power draw for the 0.254 mm cut, which used between 105 and 255 watts, was within this range, and the times when the power used for the cut was below this range reflect rust removal. As grinding is used not only for shaping but also for cleaning and finishing parts, this decreased power draw does reflect some industrial grinding situations.

While cutting, the total power used by the grinder spanned between 953 and 1148 watts. The Okamoto ACC-8-20DX is equipped with a 1500 watt spindle motor, so under typical operation, the machine was running at about two thirds of its maximum power. At the times of the greatest amount of power consumption needed for cutting, 22% of the power drawn by the

grinder actually went into the cut, 7% went into moving the worktable, 20% to keep the hydraulic pump active, 26% to keep the grinding wheel active, 19% to operate the dust fan, 2% to operate the coolant pump, and 4% to power the control box. With 22% of power actually being used to make the cut and 7% being used to position the worktable, during idle time, the grinder would still consume 71% of the amount of power it uses during active cutting, so times when a grinder is idle or positioning a piece in a production facility still consume a large amount of power. Due to the small volume of material removed during grinding, most of the energy consumed is simply used to keep the machine activated and not to remove material, as was demonstrated by these measurements. These measurements also show that this surface grinder typically operated at about two thirds of the maximum power output of its motor.

Description of Inputs and Outputs of the Grinding Process and Estimates for Energy Use and Waste Creation from U.S. Grinding

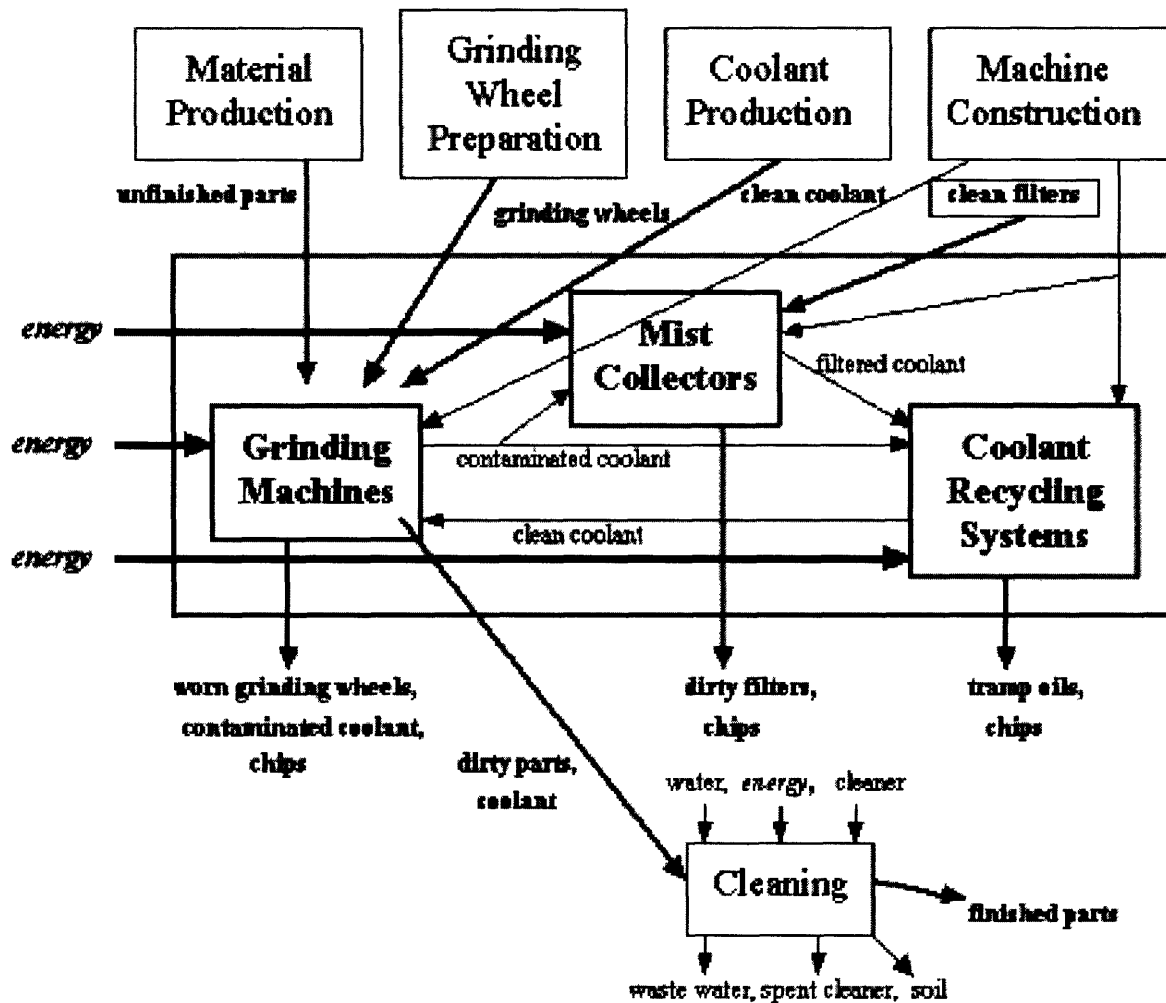


Figure 15: Summary of the inputs and outputs of the grinding process.

A summary of the process by which ground parts are produced is presented in Figure 15. The arrows represent flows of materials and energy between different phases of the process. The phases focused on in this thesis are those conducted by the machines depicted inside the large box. The total amount of energy consumed by grinding machines, coolant recycling

machines, and mist collectors each year in the United States will be calculated. A work scenario of 50 work weeks per year with 5 work days per week will be assumed. Most factories run two eight hour production shifts a day, each with a one hour break for employees, and a third shift for clean up and maintenance (Bureau of Labor Statistics, 2005), so 14 production hours per day will be assumed per day. This yields a total of 3500 production hours per year. During production hours, a machine use scenario where grinders spend 10% of their time idling and 30% of their non-idle time positioning, will be assumed (Dahmus, 2004). This means 2205 hours per year will be spent in cuts.

A review of grinding machines made by many different companies found by searching www.machinetoolsonline.com revealed the typical specifications for all different kinds of grinders. As for power consumption, surface grinders typically have 3 kW motors. Cylindrical and centerless grinders vary greatly, with internal cylindrical grinders requiring smaller motors and centerless requiring several motors, but overall they average about 8.5 kW of motors per machine. Tool and cutter machines fall on the high end at 18 kW, while polishing machines are on the low end around 2 kW. Honing and lapping machines average about 7.5 kW, while creep feed grinders tend to around 10 kW motors. If idle grinding machines are assumed to run at 67% of their maximum total power¹, then over one year, the energy consumed by grinding machine not counting the energy of material removal is 3.6×10^{15} joules per year for surface grinders, 2.2×10^{15} joules per year for cylindrical and centerless grinders, 7.5×10^{15} joules per year for tool and cutter machines, 1.5×10^{15} joules per year for polishing machines, 2.1×10^{15} joules per year for honing and lapping machines, and 7.5×10^{15} joules per year for unclassified grinders. A summary of grinder energy consumption can be seen in Figure 16.

¹ Idle refers to all systems powered and operating including the spindle, but without the grinding wheel engaged with the workpiece.

<i>Type of Unit</i>	<i>Number of Units</i>	<i>Average Motor Wattage (kW)</i>	<i>Energy Consumed (*10¹⁵ J)</i>
Surface Grinders	144263	3.0	3.6
Cylindrical/Centerless Grinders	30082	8.5	2.2
Tool and Cutter Grinders	49550	18.0	7.5
Honing and Lapping Machines	32790	7.5	2.1
Polishing Machines	89677	2.0	1.5
Other Grinding Machines	88486	10.0	7.5
<i>Total</i>	<i>434847</i>		<i>24.4</i>

Figure 16: Energy consumed by grinders in the U.S. excluding energy put into cuts, assuming 3500 work hours per year, given motors running at 67% of maximum power.

The total mass of scrap chips produced each year will be estimated and compared to an estimate of the total mass of finished parts produced each year. The average size of a part can be estimated from the maximum size which can be ground on a given machine. Grinding is used both to finish large parts and to shape very small parts, but the average part will be assumed to have dimensions of half of the maximum which can be held by a typical grinding machine. For flat surfaces ground on a reciprocating table, the average piece will be 3 meters by .5 meters in area. For round surfaces or holes, the average diameter is 1 meter. The average workpiece height is 0.125 meters. In conventional grinding, average grinding depth per pass is about .03 mm, whereas 3.5 mm per pass is typical for creep feed grinding (Kalpakjian, 2001). For grinding the upper surface of an average flat rectangular piece, the resulting mass of scrap chips is 0.02% of the mass of the initial piece. For grinding the outer surface of an average cylindrical piece, 0.01% of the mass of the starting piece is ground off into chips. Thus the mass of goods produced through grinding is very high when compared to the mass of scrap produced.

Average longitudinal, transverse, and axial feed rates for all types of grinding machines tend to be around 10 meters per minute (167 mm/sec). It will be assumed that longitudinal feed is at maximum while transverse feed is the width of the grinding wheel once per second, for a typical 2" (50.8 mm) wide grinding wheel. At maximum feed rate, average depth, and a specific

energy of $41 \text{ W}\cdot\text{s}/\text{mm}^3$ for mid grade steel, conventional material removal requires 10.4 kW of power, while creep feed grinding requires 1.2 MW of power, more than one hundred times as much as conventional grinding. Still, creep feed grinding is not pervasive enough to be included in the inventory of U.S. grinding machines, so the amount of energy consumed in material removal each year will be calculated for 100% conventional grinders. The fact that conventional grinders will often not be running at their maximum feed rate will correct somewhat for the exclusion of creep feed grinding. Given these assumptions, $36 \cdot 10^{15}$ joules per year of energy are consumed in grinding cuts. These cuts produce 876,760 cubic meters of scrap per year, which, if it were all steel, would weigh $1.5 \cdot 10^{10}$ pounds. A summary of the total amount of waste produced by grinding each year can be found in Figure 17. A summary of the total amount of energy used in grinding each year may be found in Figure 18.

Each grinder will be considered to consume 60 grinding wheels per year, each weighing two pounds (Tri-State Tool Sharpening, 2005). Although efforts are being made by companies like Mitsubishi to recycle grinding wheels and chips from grinding into road bed materials, such efforts are currently very rare, and all of these types of waste will be assumed sent to landfills (Mitsubishi Motors, 2005). Although honing and lapping machines use stones and laps instead of grinding wheels, these wear at a similar rates, and so will be considered the source of the same amount of solid waste per year. Given a total of 434,847 abrasive cutting and finishing machines in the United States (American Machinist, 1989), there are 52,181,640 pounds of spent grinding wheels sent to landfills every year.

Each mist collector will be considered to consume one prefilter and one primary filter each month, for a total of twenty four filters per year sent to a landfill for each machine. Mist cooling is typically used for tough machining conditions where the material to be cut is very abrasive,

such as during tool and cutter grinding (Littlemachineshop.com, 2004) (Master Chemical Corporation, 2004). Flood cooling is far more commonly used in the United States for other grinding operations (Aronson, 2004), so the number of oil mist collectors in use in the U.S. will be assumed equal to the number of tool and cutter grinders. The Industrial Air Solutions Modular High Performance Collector uses a 24" by 24" by 4" prefilter and a comparably sized primary filter as well as a 24" by 24" by 11.5" HEPA filter (IAS, Inc., 2005). The prefilters and primary filters, which are disposed of, weigh about 12 pounds each (LLNL, 2003). Considering that 11% of grinding machines in the U.S. are tool and cutter machines, that means a total of 49,550 oil mist collectors in use in the grinding industry, producing 14,270,346 pounds of used filters sent to landfills every year. Given 49,550 oil mist collectors with 5 HP motors operating for 3500 hours each year at 67% of maximum motor capacity, oil mist collectors in the U.S. consume 1.6×10^{15} joules of energy per year.

It will be assumed that production facilities with more than 20 employees are large enough that all their grinding fluids will be recycled, while all smaller plants discard the coolant from their grinders once a year and send it to be incinerated (Bernard, 2005). Of course, large plants will lose some fluids every year in the form of tramp oils or grinding fluids that stick to chips which are thrown away, but some smaller plants will hire outside companies to recycle their fluids. Neither of these factors should offset estimates too significantly. An analysis of the amount of water used each year to reconstitute dilute metalworking fluids has already been conducted (Dahmus, 2004). Of the 89% of grinders that are not tool or cutter machines, 24% are in production facilities with less than 20 employees, for a total of 92,132 grinding machines. Grinding machines can vary greatly in their grinding fluid capacity, from the 159 gallon Micron CNC centerless grinder (F. P. Miller, 2005) to the 1 gallon Okamoto OGM-820PB cylindrical grinder. Other cylindrical grinders might have up to 150 gallons of coolant capacity, though a

small production facility which does not recycle its fluids would likely not use such a machine. Grinder coolant capacities tend to cluster around 1, 20, 50, or 150 gallons, regardless of grinder type (Okamoto, 2005). The average grinder in a production facility with less than 20 people will be assumed to have a coolant capacity of 25 gallons. If the coolant in each of these grinders is replaced once a year and the spent fluids are sent to be incinerated, 2,303,312 gallons of grinding fluids are incinerated each year.

Spent grinding wheels	52,181,640 lb.
Dirty air filters	14,270,346 lb.
Scrap chips	15,141,664,775 lb.
<i>Total solid waste</i>	<i>15,208,116,761 lb.</i>
Discarded coolant	2,303,312 gal.

Figure 17: Total waste produced by grinding.

The number of coolant recycling systems will then be proportional to the number of grinding machines that are not tool and cutter machines and in plants with more at least 20 workers. This is 89% of grinders in the 76% of plants with 20 or more workers, or 293,165 grinding machines. If each of these machines is operating at the typical coolant flow rate of 2.64 gallons per minute and coolant recycling systems have motors of size .3 HP per gallon per minute cleaned, and the coolant recycling systems are assumed to run at 67% of maximum motor capacity, the sum total of coolant recycling systems in the country draws 154,791 HP (115 MW). Over the yearly work scenario, coolant recycling systems consume 1.4×10^{15} joules of energy.

	<i>Energy Consumed (*10¹⁵ J)</i>
Grinding Machines (not cutting)	24.4
Cutting	35.9
Coolant Recycling Systems	1.4
Mist Collectors	1.6
<i>Total</i>	<i>63.4</i>

Figure 18: Total energy consumption due to grinding.

The energy required to machine, cast, or otherwise create the rough parts sent into grinders has been the subject of other studies (Dahmus, 2004) (Dalquist, 2004) and will not be included in this analysis. As the machines involved in the process being studied have useful life spans of around twenty years, the resources required to build the machines are not a significant enough factor to evaluate. The resources required to produce grinding coolants and those required to collect, shape, and fire the materials to produce grinding wheels will also not be included in this study, nor shall the process of cleaning parts after they have left the grinding facility.

In total, including all types of grinding machines, coolant recycling systems, and oil mist collectors, 63×10^{15} joules of energy are consumed per year by grinding in manufacturing, 57% of which is directly used in material removal. In total, 1.5×10^{10} pounds of scrap chips, spent grinding wheels, and used filters are produced each year as a result of grinding, over 99% of that being scrap chips. In the name of keeping such vast quantities of waste out of landfills, efforts should be made to clean and recycle grinding chips, a practice which is currently rare. Although most grinding fluids are recycled, about 2.3 million gallons of fluids per year are incinerated.

Conclusion

Grinding is an ideal method for producing parts with a fine surface finish and high dimensional accuracy and for shaping hard or brittle workpieces. There are a wide variety of different types of grinding machines, each with different applications and slightly different energy requirements. Workpieces are generally flooded with a stream of coolant while being ground or placed in a spray of coolant mist. Coolant recycling systems are used to filter ground off chips out of coolant and to remove foreign oils and bacteria which pose health hazards. Oil mist collectors both clean mist coolant and prevent the toxic coolant from being inhaled by machinists. These systems also consume significant amounts of energy. In total, 63×10^{15} joules of energy are consumed per year by grinding in manufacturing, 57% of which is directly used in material removal. Despite the relatively small depths of material removed from ground parts, usually less than 1 mm, grinding still creates a large amount of solid waste. In total, 1.5×10^{10} pounds of scrap chips, spent grinding wheels, and used filters are produced each year as a result of grinding, over 99% of that being scrap chips. Although most grinding fluids are recycled, about 2.3 million gallons of fluids per year are incinerated. Further resources are required to cast and machine the rough parts sent to grinders and to clean parts after they have been ground. Grinding wheels, coolants, and machine tools must all be manufactured, and power plants must expend resources to create the energy needed to power grinding machines. Grinding creates a significant environmental footprint, creating a need for methods to reduce energy use in grinding and for ways to recycle solid waste that would otherwise be sent to landfills or incinerated. Unfortunately, as grinding machines are a large capital expense replaces infrequently by production centers, changes in grinding technology may be slow to bring about.

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