Basics of Mechanical Engineering-2

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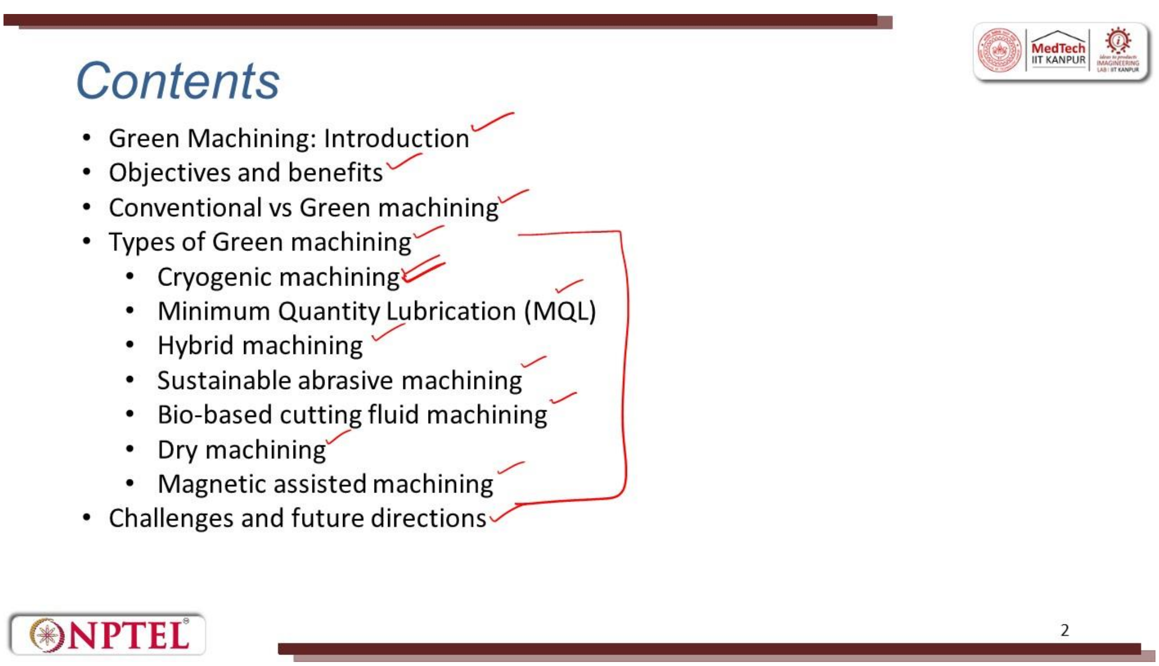
Week 12

Lecture 50

Green Machining

Welcome to the next lecture in the last week of the course Basics of Mechanical Engineering 2. We are discussing sustainable engineering and sustainable manufacturing this week. I have talked about unit manufacturing processes. I have talked about life cycle assessment in the previous lectures. In the unit manufacturing process, there are various kinds, such as machining.

It includes casting, forging, assembly, welding—anything that happens at a single workstation is a unit manufacturing process. I will focus this lecture specifically on green machining. There are certain strategies for green machining. When you say green machining, we are talking about technologies that have been developed to reduce energy consumption, improve quality, or reduce pollution generated in the machining process.

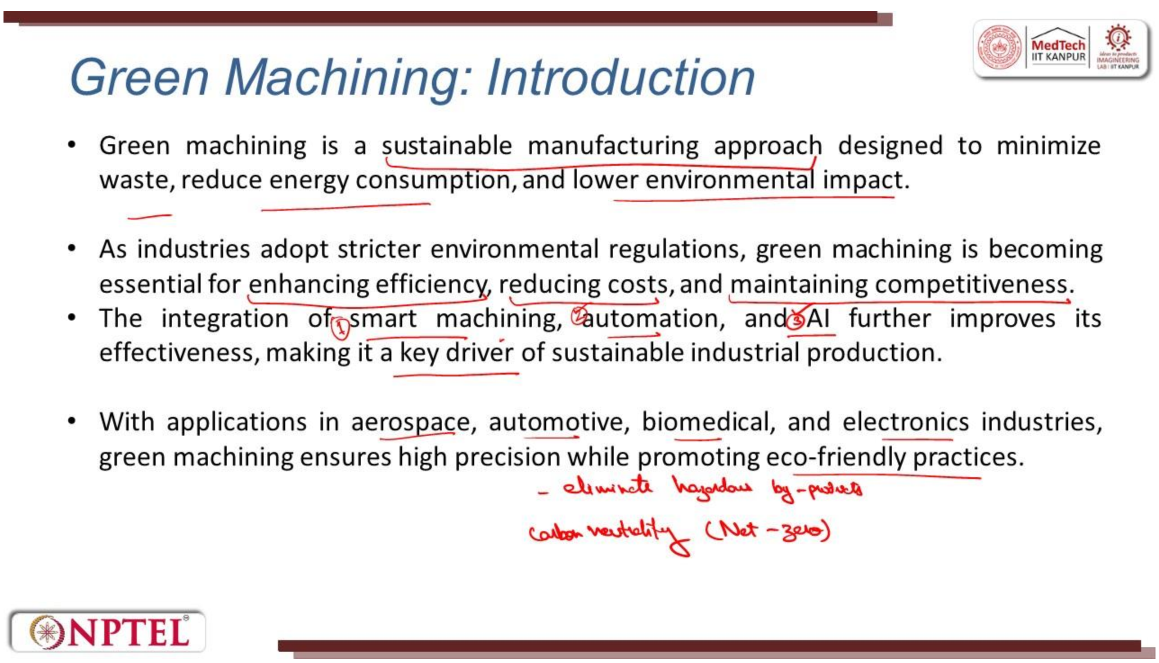


So, the contents of the lecture flow like this: introduction to green machining, objectives and benefits of green machining, conventional versus green machining methods. We will try to see the difference. Then, types of green machining. I will discuss these very briefly: cryogenic machining, minimum quantity lubrication method, hybrid machining systems, sustainable abrasive machining, and bio-based cutting fluid machining.

Dry machining and magnetic adjacent machining. Then certain challenges which are nowadays coming. Through these technologies which are there and future directions. Only a brief introduction each of them itself is a big technology on which certain doctoral thesis have been written. Certain researches have happened in the industry.

And people are still developing, for example in cryogenic machining only. Lot of further research is happening like how to store liquid nitrogen. How to put liquid nitrogen into a portable setup. How to use this specifically for one setup only. When generally liquid nitrogen setup is used.

A big setup or big plant is there that supplies this liquid nitrogen to the various workstations. Wherever this machining is required, cryogenic machining is required. Now, lot of further research is going on. But I will give you a very brief introduction to what these are green machining.



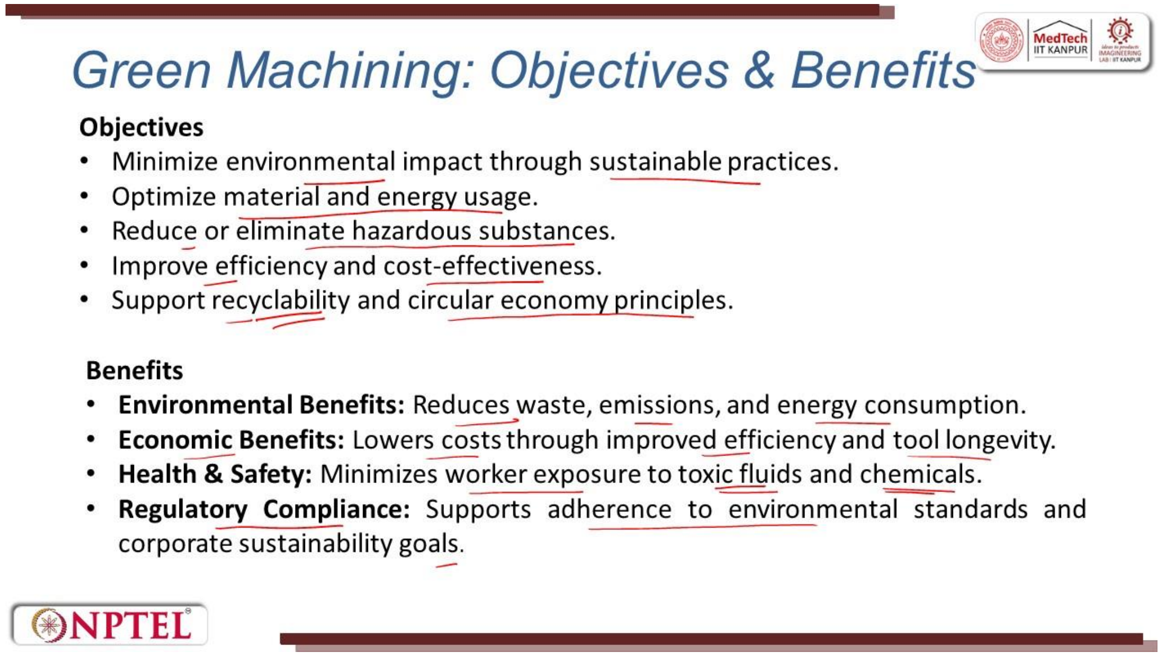
It is a sustainable manufacturing approach designed to minimize waste, reduce energy consumption and lower environmental impact. Just a generic definition, as we saw for green manufacturing itself. As industries adopt stricter environmental regulations, green machining is becoming essential for enhancing efficiency, reducing costs, and maintaining competitiveness.

The integration of smart machining, automation, and AI further improves its effectiveness. Smart machining is when the machine tries to understand what the next step is.

Given the complete CNC code, it tries to understand that this whole component would be completed in one go. It is a smart machine system automation. Using CNC itself is automation. Then, when the component is completed, how do we sort the components? How do we try to remove or take out the defective components?

That is an automated system based upon sensors. AI would further develop its own programs, which will help us take all the smart machining and automation to a different level. This makes it a key driver for sustainable industrial production. With applications in aerospace, automotive, biomedical, and electronics industries.

Green machining ensures high precision while promoting eco-friendly practices. So what we do is eliminate the hazardous byproducts. And we align with the global effort toward carbon neutrality that I have talked about. Carbon neutrality, which is net zero, was discussed in the last lectures. And circular economy principles are further utilized. So this is important in green machining.



The objectives of clean machining are to minimize environmental impact through sustainable practices. Optimize material and energy usage, and reduce or eliminate hazardous substances. As I just mentioned, improve efficiency and cost-effectiveness, and support recyclability and circular economy principles. Recyclability means that when we use the material, it should be recyclable.

Benefits: environmental benefits—reduces waste, emissions, and energy consumption; economic benefits—lower costs and improved efficiency. And longevity, health, and safety—minimizes workers' exposure to toxic fluids and chemicals. Which involves working with vegetable fluids, bio-based cutting fluids that are organic. Or those that are biodegradable—this is also a focus here. Exposure to toxic fluids and chemicals is reduced here. Regulatory compliance is also present. It supports adherence to environmental standards and corporate sustainability goals.

Conventional vs Green Machining

Aspects	Conventional Machining	Green Machining
Environmental Impact & Waste	High pollution, excessive material waste, and resource consumption	Minimal waste, reduced emissions, and sustainable resource use
Energy & Cost Efficiency	Higher energy usage and operational costs due to inefficiencies	Lower energy consumption and costs through optimized machining
Cutting Fluids & Worker Safety	Relies on large quantities of lubricants, exposing workers to hazards	Uses dry machining, MQL, or cryogenic cooling, enhancing safety
Tool Wear & Life	More wear due to friction and overheating, leading to frequent replacements	Longer tool life with advanced coatings and eco-friendly lubricants
Material Utilization	Significant scrap generation from inefficient processes	Optimized cutting paths reduce waste and improve material usage

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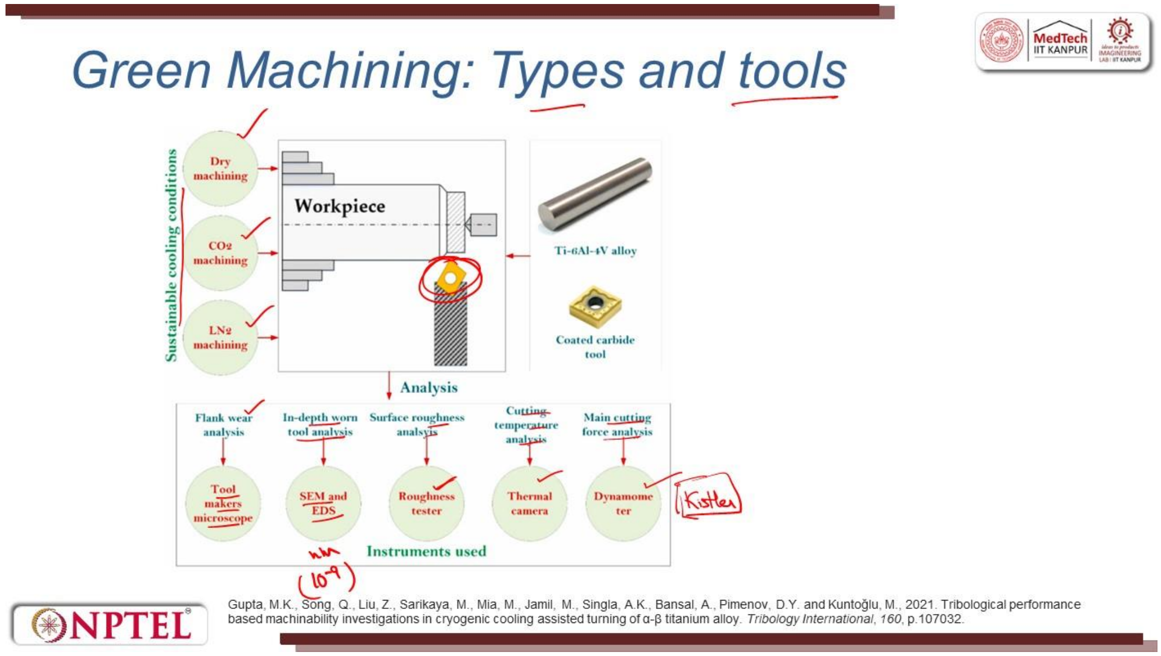
Difference between conventional and green machining. As we saw in the previous slides, environmental impact. Waste in green machining is minimal, with reduced emissions and sustainable resource use.

However, in conventional machining, pollution is high, and excessive material wastage occurs. Resource consumption is also high, but energy and cost efficiency are better, with lower energy consumption.

Reduced cost is achieved through optimized machining and cutting fluids. Green machining relies on dry machining, minimum quantity lubrication, cryogenic cooling, and enhances worker safety. Tool wear and tool life: longer tool life with advanced coatings and eco-friendly lubricants is present in green machining.

Material utilization: significant scrap is generated in conventional machining, but cutting paths are optimized. We reduce waste and improve material usage in green machining. This is a green machining type where different kinds of fluids or cooling conditions can be used. You can see here. Sustainable cooling conditions include dry machining, which means not using fluid at all. Then carbon dioxide machining uses carbon dioxide gas only. And no collecting fluid is used; then we use liquid nitrogen, which is cooled.



So here are different types and tools. When I talk about tools, I mean the equipment or the gadgets. These are used to monitor this green machining. Some examples here are, for instance, the flank.

For analysis of the tool, we use a toolmaker's microscope. In-depth worn-tool analysis is done by SEM or EDS. These images help us examine the structure of the worn area down to the nanometer level. That is 10 raised to the power of minus 9. For surface stress analysis, roughness testers are available.

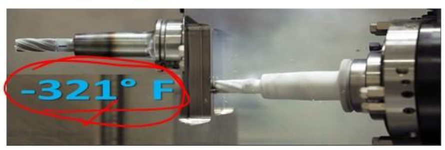
They are developed by Mitutoyo and many other companies, which help us understand or analyze surface stress. For cutting temperature analysis, thermal cameras are used. There are optical thermal cameras. There are thermocouple-based temperature measuring devices that can be used. Then, maintaining or understanding or monitoring the cutting force analysis.

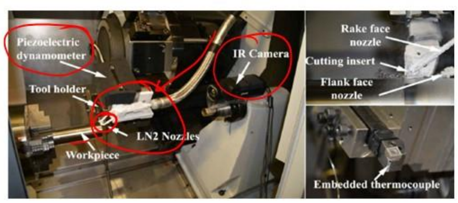
Thermometers are there. Mostly manufactured by Kistler. Certain kinds of dynamometers measure in three dimensions. Only three coordinates, then rotary. Different kinds of dynamometers are there. That helps us to understand, calculate, monitor, or capture the force applied for this specific machining. If the force is high, the energy consumption is also high. So that could be monitored here.

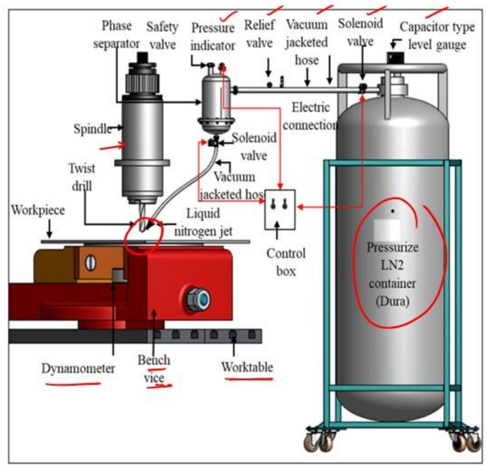
Cryogenic Machining

- **Working Principle:** This technique uses cryogenic coolants such as liquid nitrogen (LN_2) or carbon dioxide (CO_2) to rapidly lower the cutting zone temperature, preventing thermal damage to the workpiece and cutting tool.
- **Key Features:** Eliminates conventional cutting fluids, enhances tool life, reduces friction and heat generation, and improves machining accuracy.
- **Advantages:** Suitable for machining high-strength materials like titanium and Inconel, enhances tool durability, improves surface finish, and reduces environmental impact.
- **Limitations:** High initial investment, requires specialized storage and handling for cryogenic fluids, and demands additional safety measures.
- **Applications:** Aerospace (titanium and superalloy machining), biomedical industry (prosthetic implants), automotive (lightweight alloy machining), and precision manufacturing.

Cryogenic Machining







Qian, C., Fan, Z., Tian, Y., Liu, Y., Han, J. and Wang, J., 2021. A review on magnetic abrasive finishing. *The International Journal of Advanced Manufacturing Technology*, *112*, pp.619-634.

Next is cryogenic machining, one of the green machining methods. This technique uses cryogenic coolants. These coolants could be liquid nitrogen (LN2) or carbon dioxide.

That is CO2, which rapidly lowers the cutting zone temperature, preventing thermal damage to the workpiece and cutting tool. Key features: it eliminates conventional machining cutting fluids, enhances tool life, and reduces friction and heat generation. Furthermore, it helps to improve machining accuracy with certain advantages. As mentioned in the key features, high-strength materials such as titanium. And Inconel could be machined here while maintaining the surface finish.

And it enhances the tool durability and reduces environmental impact titanium is a tool for machining the titanium. We cannot use simply high-speed steel tools. Very high strength tools are to be used. But in cryogenic machining when we try to use the tool wear is very less. So that is why the tool durability is high.

We will try to use cryogenic systems limitations high initial investment. Because this requires specialized storage and handling for the cryogenic fluids. And this demands additional safety measures as well. Because if leaked the cryogenic fluids such as liquid nitrogen could be harmful to the person who is using it. So these are stored in very closed or very strong cylinders applications.

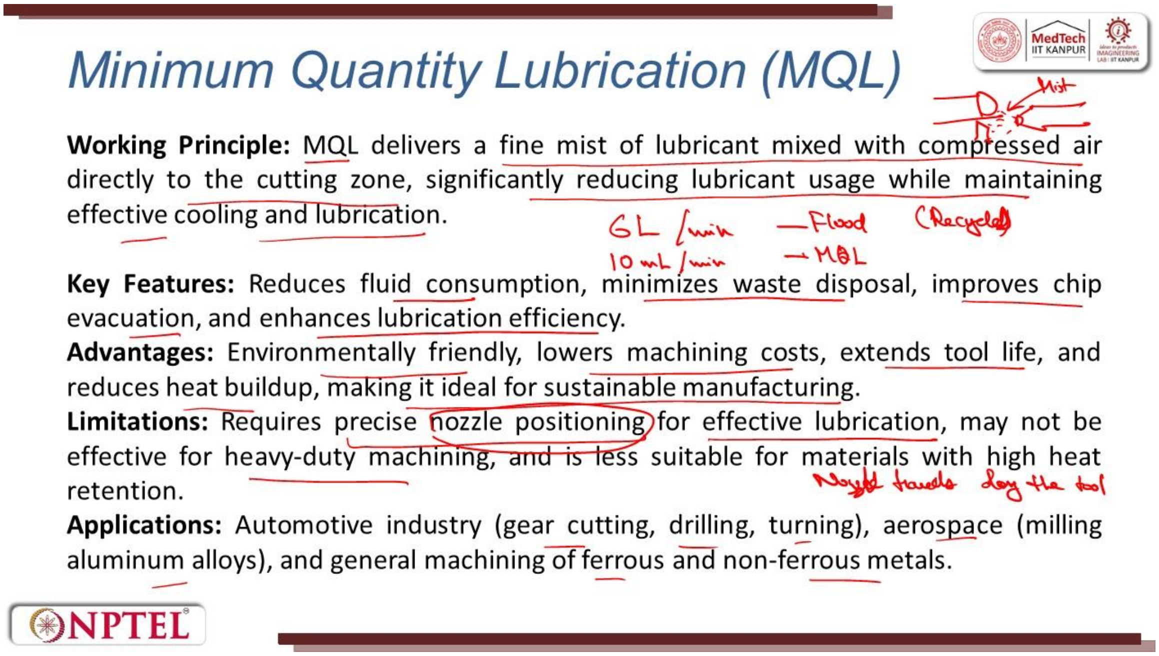
Aerospace, titanium, super alloy machining, biomedical industry, prosthetic implants, automotive lightweight alloy machining and precision manufacturing. These are all applications where cryogenic machining is used. So this is one illustration representing the liquid nitrogen at minus 321 degree Fahrenheit. And this is how does it look like when we are trying to do this cryogenic machining. So this is liquid nitrogen nozzle.

So through this pipe liquid nitrogen is being supplied. And through this nozzle it is being applied at the tool work interface. This is work piece. This is tool. At this interface the cryogenic fluid is implied.

And this dynamometer is measuring the force. There is an IR camera which is also monitoring the temperature. It is only telling that this temperature is 321 degree centigrade. So, there are embedded thermocouple there are rake phase nozzle cutting insert flange nozzle. These are all given taken from a study.

Now, this setup gives how is liquid nitrogen stored here it is pressurized container. And from here liquid nitrogen is up supplied and there are components of this container. As well pressure indicator helps us to control the pressure indicator. And this solenoid walls helps us to control the supply of nickel nitrogen. And it is exactly supplied at the point where final machining has to happen.

This is drilling example here the spindle will rotate and twist drill will try to do machining. While cryogenic fluid is being supplied here and the force is being monitored using a dynamometer. Which is all held on bench wise. And this bench wise is further held on a work table.



Next is Minimum Quantity Lubrication. Working principle is minimum quantity lubrication. That delivers fine mist of lubricant mixed with compressed air directly to the cutting zone. Significantly reducing the lubricant usage while maintaining effective cooling and lubrication. In the case of the cutting fluid application when there is a flood application. The fluid application rate could be 6 litres per minute.

This is flood though this is recycled on the other hand minimum quantity lubrication could even supply fluid up till 10 milliliters per minute. This is mql minimum quantity lubrication. So here the mist is generated. This mist, how is this generated? Using a specific nozzle in through which the compressed air get the cutting fluid pass through.

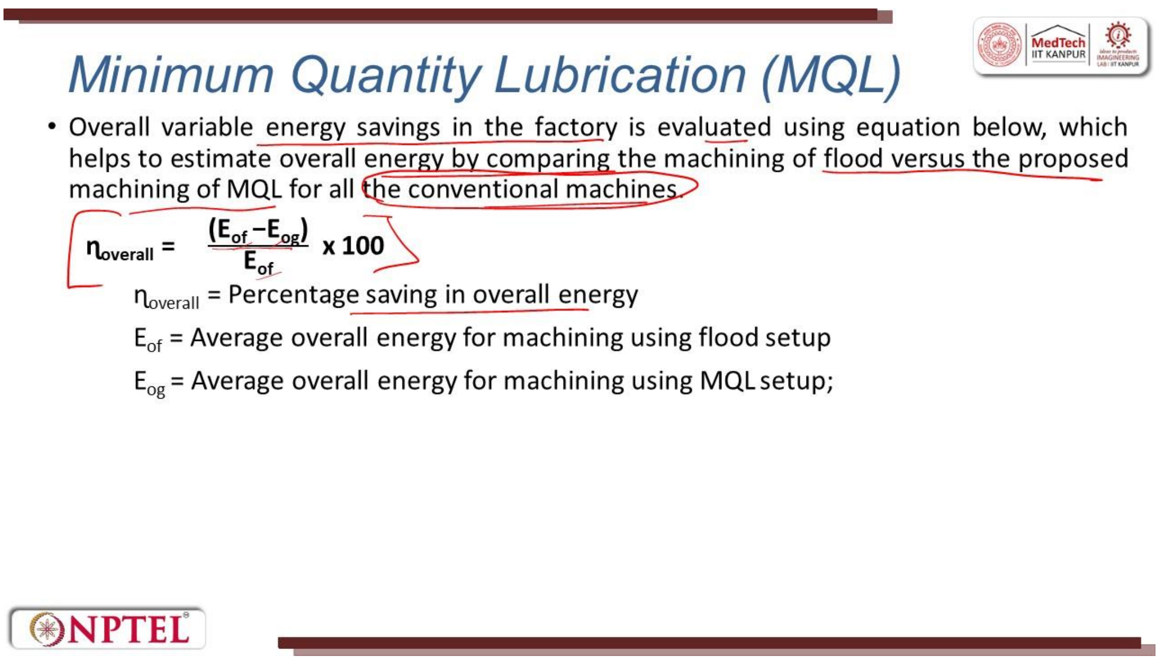
But this is applied specifically in a tool-work interface again. So this reduces fluid consumption, minimizes waste disposal, improves chip evacuation, and enhances lubricating efficiency. Advantages: environmentally friendly, lowers machining costs, extends tool life, and reduces heat buildup. Making it ideal for sustainable manufacturing. Limitations: it requires precise nozzle positioning for effective lubrication.

Because when we are talking about minimum quantity lubrication, If this is the tool-work interface, this is the work, and here we have a tool that is doing its machining. The mist nozzle has to supply fluid specifically here. So this is mist here. So application, that is the nozzle positioning.

And this nozzle has to travel along the tool. Nozzle travels along the tool. This may not be effective for high-velocity machining. As it is less suitable for materials with high heat retention. Automotive industry: gear cutting, drilling, turning; aerospace: milling of aluminum alloys.

And general machining of ferrous and non-ferrous metals are some of the examples here. In one of the studies on minimum quantity lubrication systems, The energy was captured using a dynamometer. First, the cutting fluid was used to perform a specific kind of machining. And for the same machining, minimum quantity lubrication was used.

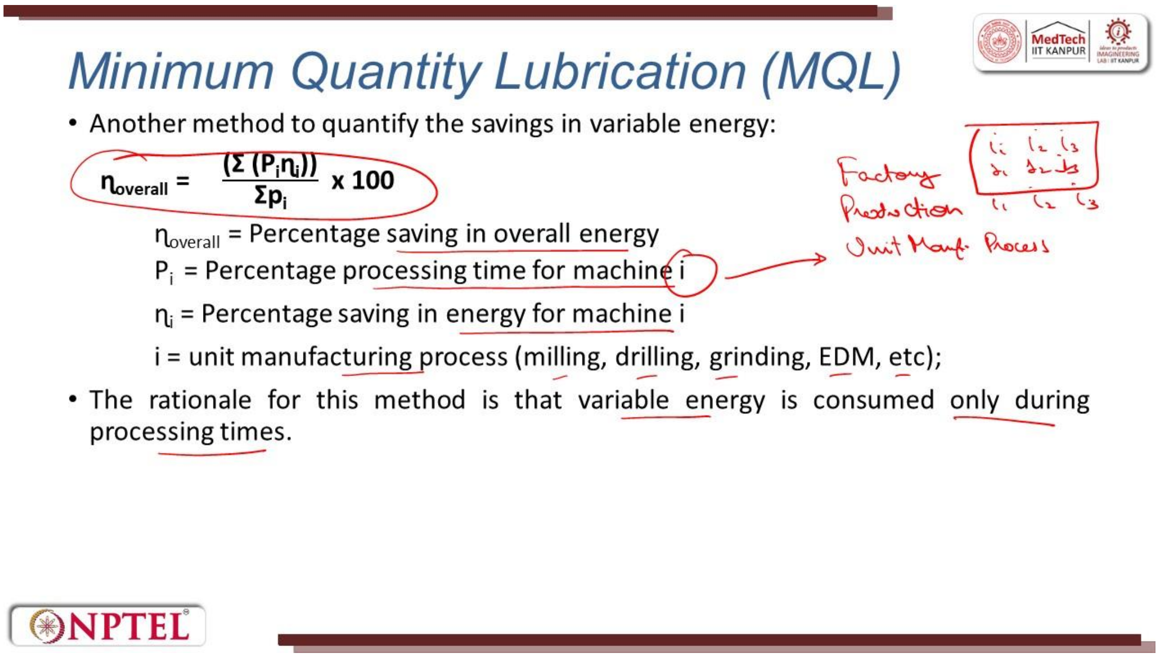
When I say energy, the force was captured using the dynamometer. Then this force was translated or converted into proportional energy, That is consumed for applying this force.



Now, in this, the overall variable energy savings in a factory is evaluated using an equation. Below, which helps to estimate overall energy by comparing the machining of flood, Versus the proposed machining of MQL for all the conventional machines in the whole factory. All the conventional machines when I talk about minimum quantity lubrication, and basically talking about the conventional systems only. So overall energy or percentage saving in overall energy is:

$$\eta_{overall} = \frac{(E_{of} - E_{og})}{E_{of}} \times 100$$

This is the percentage of the overall energy saving.



Similarly, for the n number of machines, this could be put as:

$$\eta_{overall} = \frac{(\Sigma (P_i \eta_i))}{\Sigma p_i} \times 100$$

$\eta_{overall}$ = Percentage saving in overall energy

P_i = Percentage processing time for machine i

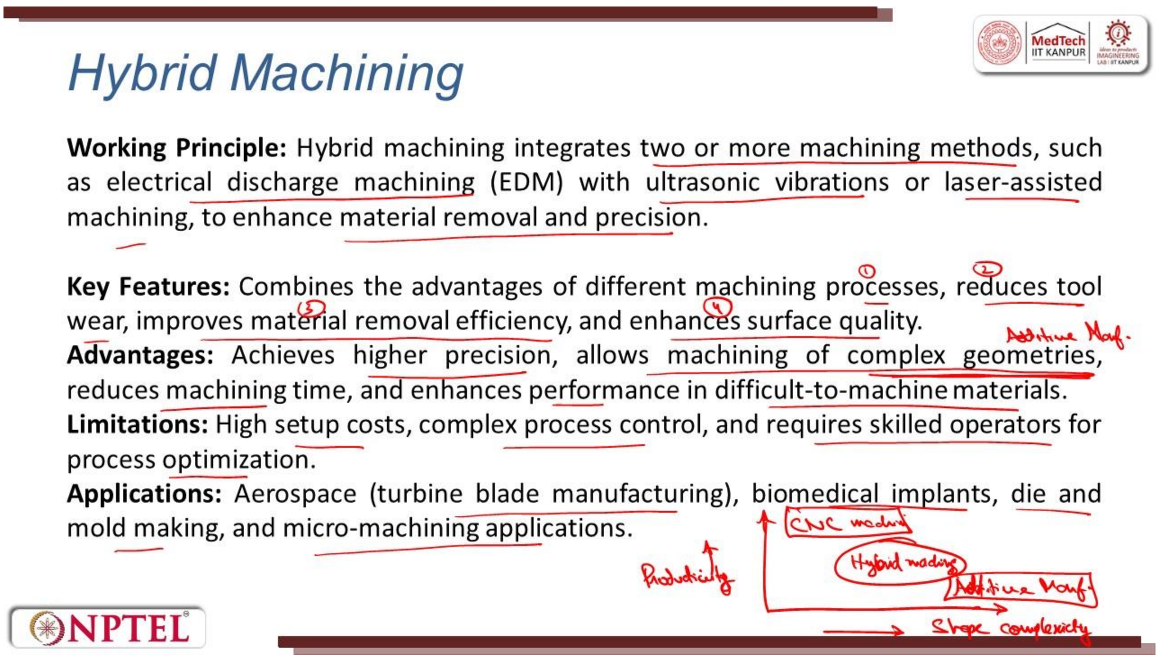
η_i = Percentage saving in energy for machine i

i = unit manufacturing process (milling, drilling, grinding, EDM, etc);

The rationale for this method is that variable energy is consumed only during processing times. So, as I talked about the unit manufacturing process in the previous lectures, there is a factory level. There is a production line. And there is a unit manufacturing process. So, this is specifically I, one unit manufacturing process, and a number of unit processes are there that make one production line. For example, i1, i2, i3, these make a production line, and a number of i's and j's: I1, 2, 3.

Then it could be j1, j2, j3; this makes a complete factory. For the overall factory, this percentage could be calculated from the unit malfunctioning process. Similarly, the saving in the cutting fluids. For example, as I said, liters per minute and milliliters per minute—around a thousand times down. So this could also be calculated: the difference in the cutting fluid consumed using the first setup.

And the cutting fluid using vacuum setup per unit, the cutting fluid used in the flood setup into 100. This is the percentage saving in cutting fluid.



Next is hybrid machining. Hybrid means when we are talking about something between two things. That is, we try to combine the advantages of two different systems.

That is, maybe additive manufacturing and CNC manufacturing put together as a hybrid system or EDM. And magnetic setup put together as a hybrid system or cryogenic machining. And magnetic-based machining put together becomes a hybrid system. So hybrid machining integrates two or more machining methods. Such as EDM (electric discharge machining) with ultrasonic vibrations.

Or laser-assisted machining enhances material removal and precision. Key features are: It combines the advantages of different machining processes, reduces tool wear, and improves material removal efficiency. It also enhances surface quality. Advantages include higher precision. It allows machining of complex geometries. Complex geometries mean additive plus CNC manufacturing.

If you try to bring them together, it is something like this. Suppose we have CNC machining here. And we have additive manufacturing here. I am talking about how productivity in CNC is higher. Productivity goes in this direction.

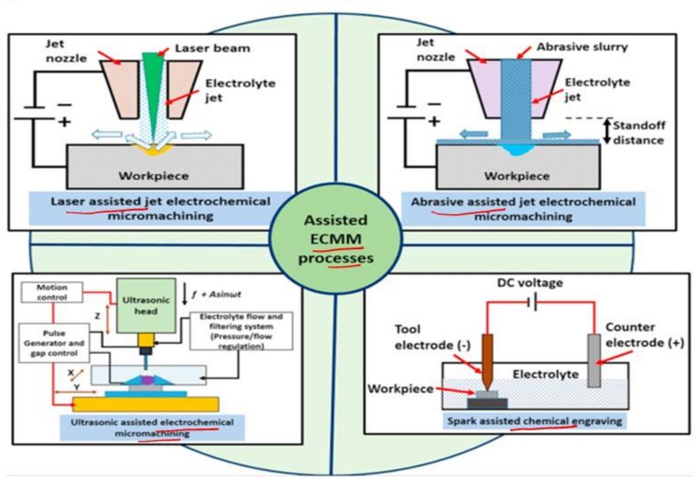
However, shape complexity is better achieved in additive. In between, we can have a system that is hybrid machining. That takes advantage of both CNC and additive. Complex shapes could be manufactured using additive manufacturing. And further productivity could be improved using CNC machines. That is, complex geometries could also be handled using additive manufacturing.

It reduces machining time and enhances performance in difficult-to-machine materials. Limitations include high setup costs and complex process control. It requires skilled operators for process optimization. Applications include turbine blade manufacturing. Turbine blade shapes are not very easy to reach.

Even 5-axis machines find it tough to make specific kinds of turbine blades to achieve the final efficiency in the propeller. That is the application where the blades are used. So, to manufacture these turbine blades, additive manufacturing could be used. To develop the hub further, CNC machining could be used. For biomedical implants, which also have complex shapes, die and mold making is required.

Quick die and mold making could be done through additive manufacturing. Through additive manufacturing, it could then be taken to CNC manufacturing.

Hybrid Machining: Classification



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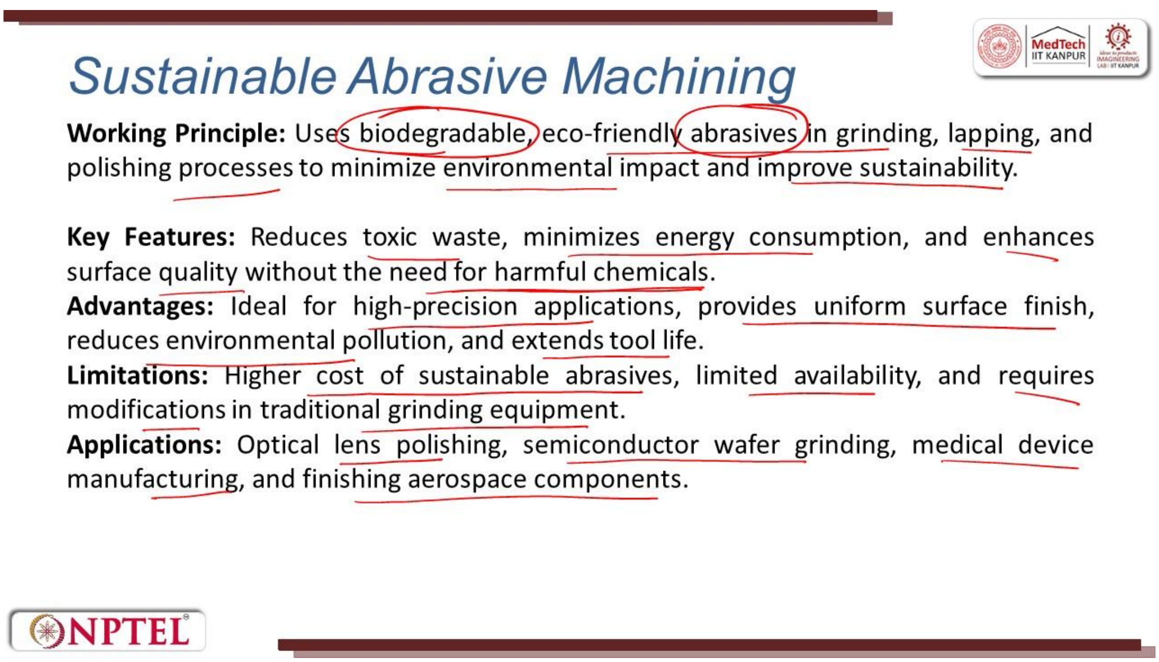
Bhattacharyya, B. and Doloi, B., 2019. Modern machining technology: Advanced, hybrid, micro machining and super finishing technology. Academic Press.

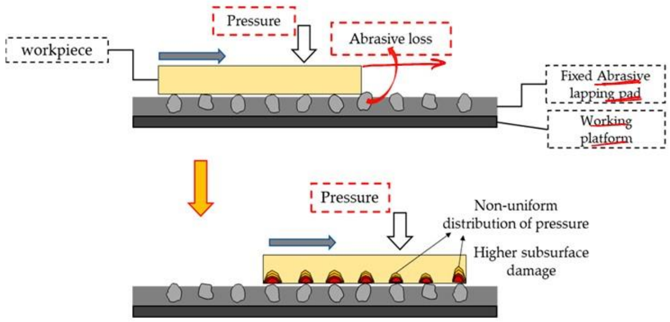
Micro-machining applications exist. Also, certain examples of hybrid machines exist. Where this electrochemical micro-machining process is assisted by various other machines.

This here is an assistance is making through laser assisted jet in electrochemical machining. You can see laser beam is there and machining is happening through electrochemical. Plus laser beaming is also further adding to the machining part. Here an assistance is being taken through abrasives as well. The abrasives are being supplied through this slurry.

And in this electrochemical setup abrasives helps us to further improve the machining. Here ultrasonic assisted electrochemical machining is there that is electrochemical ECM is going on. But ultrasonic head is also trying to vibrate and try to do more machining using some abrasive fillery here. And also spark assisted chemical engraving that is also there. These are some of the examples of hybrid machining here.



Sustainable Abrasive Machining

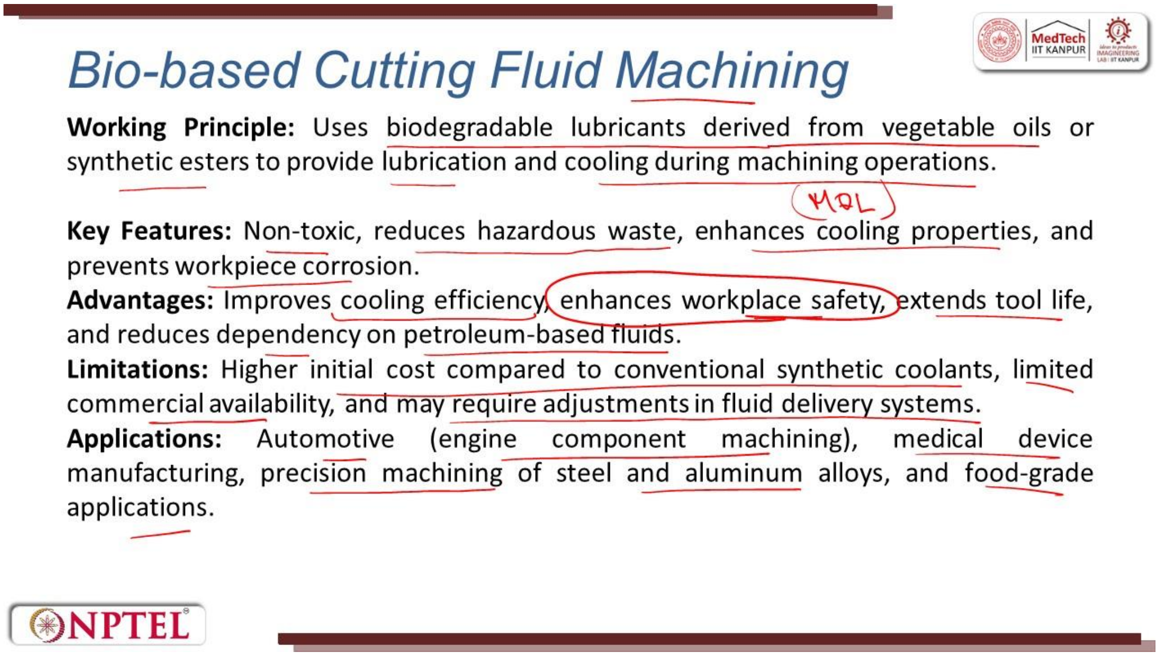


Rana, V., Petare, A.C. and Jain, N.K., 2020. Advances in abrasive flow finishing. *Advances in Abrasive Based Machining and Finishing Processes*, pp.147-181.

Next comes sustainable abrasive machining. It uses biodegradable eco-friendly abrasives in grinding, lapping, polishing processes to minimize environmental impact and improve sustainability. Here the keyword is biodegradable or eco-friendly abrasives. This helps to reduce toxic waste, minimize energy consumption and enhances surface quality without the need for the harmful chemicals. Advantages are it is ideal for high precision applications it provides uniform surface finish reduces environmental pollution and extends to life.

Higher cost of sustainable abrasives is one of the limitations further limited availability. And requires modification in traditional grinding equipment is also there when we talk about grinding abrasives. Which are biodegradable that is we use natural abrasives. Example walnut covers, baking soda. Its availability is very less, though these are biodegradable.

These have come from the natural sources only. Applications are optical lens polishing, semiconductor wafer grinding, medical device manufacturing, finishing in aerospace components or so. So this is a generic sustainable abrasive machining setup because the availability is very less. So it is put here. You can see a fixed abrasive lapping pad and working platform here. So abrasive loss is there and through pressure the workpiece is being reciprocated over it and finishing is happening.



Next comes Bio-Base Cutting Fluid Machining. It uses biodegradable lubricants derived from vegetable oils or synthetic esters to provide lubrication and cooling during machining operations. These are non-toxic. These reduce the hazardous waste, enhances cooling properties and prevents workpiece corrosion.

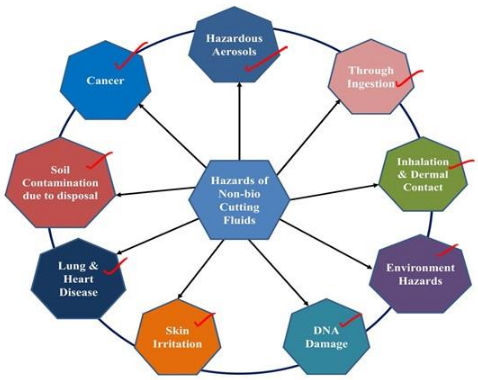
It improves cooling efficiency, and biodegradable lubricants would also be used with the MQL system. It enhances workplace safety, extends tool life, and reduces dependency on petroleum-based fluids. One issue is the long-term disposal of cutting fluids, particularly synthetic cutting fluids. These are harmful to the environment. The second level, or the lower level, is that during machining, the cutting fluid turns into mist.

That mist is harmful to the workplace where you are working. If it is vegetable oil, it is less harmful. So, it extends or enhances workplace safety as well. Limitations include higher initial cost compared to conventional synthetic coolants and limited commercial availability. They may also require adjustments in the fluid debris system, not to mention limited commercial availability.

There are also political systems or regulations where cutting fluids are sometimes not allowed for manufacturing purposes. Because those are meant for edible purposes only, such as food. Applications include automotive engine components machining, medical device manufacturing, precision machining of steel and aluminum alloys, and food-grade applications, etc.

Bio-based Cutting Fluid Machining

Hazards of non-bio cutting fluids



Bhattacharyya, B. and Doloi, B., 2019. Modern machining technology: Advanced, hybrid, micro machining and super finishing technology. Academic Press.

If bio-based cutting fluids are not used, there are certain hazards associated with non-bio-cutting fluids, such as synthetic cutting fluids. The hazards of non-bio-cutting fluids include hazardous aerosols, which are generated, as I just mentioned.

The environment around the machine becomes harmful. Through ingestion, it gets inside, and there is a chance of cancer as well. Inhalation or dermal contact causes environmental hazards, DNA damage, and skin irritation. Specifically, irritation in the eyes, lung and heart disease, and soil contamination due to disposal occur. So, the use of non-biocutting fluids

After machining and during machining, during machining. There is evaporation, in which the operator may develop certain diseases such as lung cancer or respiratory issues. I would list here eye rashes and so on, etc. When these are disposed of, these contaminated cutting fluids create water pollution and soil pollution. These are health effects.

Environmental destruction and cleaning of this fluid, including treatment, also require cost and energy. That is why biodegradable cutting fluids are emphasized.

Dry Machining

Working Principle: Eliminates the use of liquid coolants by relying on advanced tool materials, coatings, and optimized cutting parameters to manage heat generation.

Key Features: Reduces environmental pollution, eliminates coolant-related costs, improves workplace safety, and enhances machining efficiency.
Advantages: Cost-effective, eliminates coolant disposal issues, environmentally friendly, and minimizes contamination in sensitive applications.
Limitations: Requires heat-resistant cutting tools, may lead to higher tool wear in aggressive machining operations, and is less suitable for heat-sensitive materials.
Applications: Aerospace (machining aluminum and titanium alloys), automotive (engine components), and electronics (circuit board fabrication).

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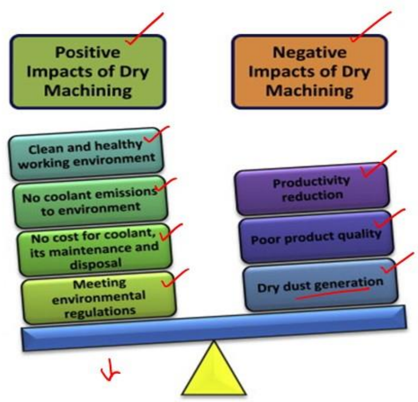
Dry Machining



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Another alternative is Dry machining, though not applicable for all materials. Where the thermal properties or thermal conductivity is very low. For example, in titanium, dry machining cannot be done.

But generally, dry machining does not use cutting fluid at all. It eliminates the use of liquid coolers by relying on advanced tool materials. Such as coatings and optimized cutting parameters to manage heat generation. Key features are it reduces environmental pollution, eliminates coolant-related costs, improves work safety, and enhances machine efficiency. Definitely, it is cost-effective, eliminates coolant disposal issues, is environmentally friendly, and minimizes contamination in sensitive applications.

Limitations are because cutting fluid is not used at all. There is no lubrication, and there is also no heat loss that goes to the cutting fluid. Only heat-resistant cutting tools are required. This is very important here. It may lead to higher tool wear in aggressive machining.

Only for finishing could it be okay. And it is less suitable for heat-sensitive materials, which I just mentioned. Applications are in aerospace engineering. For example, machining of aluminum, titanium alloys, automotive engine components, and electronics, such as circuit board fabrication. So, positive impacts of dry machining, negative impacts of dry machining.

Productivity reduction is there that is a negative point. Poor product quality could be there. Dry dust generation could be also there because for example in grinding when we use dry machining a lot of dust would be generated. And when we use flood application this will flow with the cutting fluid. So that is not there so dry dust is generated but positive impacts are clean and healthy work environment, no coolant emissions environment, no cost for coolant. And its maintenance and disposal meeting environmental regulations. So these are heavy.

Magnetic-assisted Machining

Working Principle: Uses magnetic fields to control the movement of abrasive particles or machining tools, reducing friction and improving material removal efficiency.

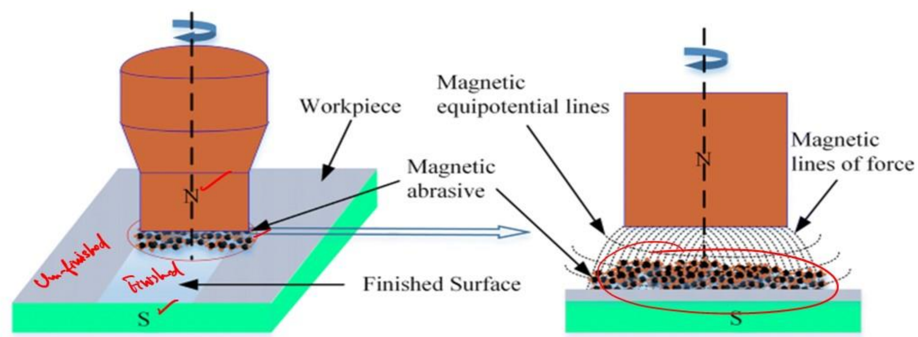
Key Features: Enhances machining accuracy, improves tool life, and enables non-contact machining for delicate components.

Advantages: Ideal for precision machining, reduces tool wear, provides better surface finish, and minimizes mechanical stress on the tool.

Limitations: Requires specialized equipment, limited to materials with magnetic properties, and may not be effective for non-ferrous metals.

Applications: Precision manufacturing of micro-components, biomedical implants, aerospace parts, and high-accuracy electronic components.

Magnetic-assisted Machining



Qian, C., Fan, Z., Tian, Y., Liu, Y., Han, J. and Wang, J., 2021. A review on magnetic abrasive finishing. *The International Journal of Advanced Manufacturing Technology*, *112*, pp.619-634.

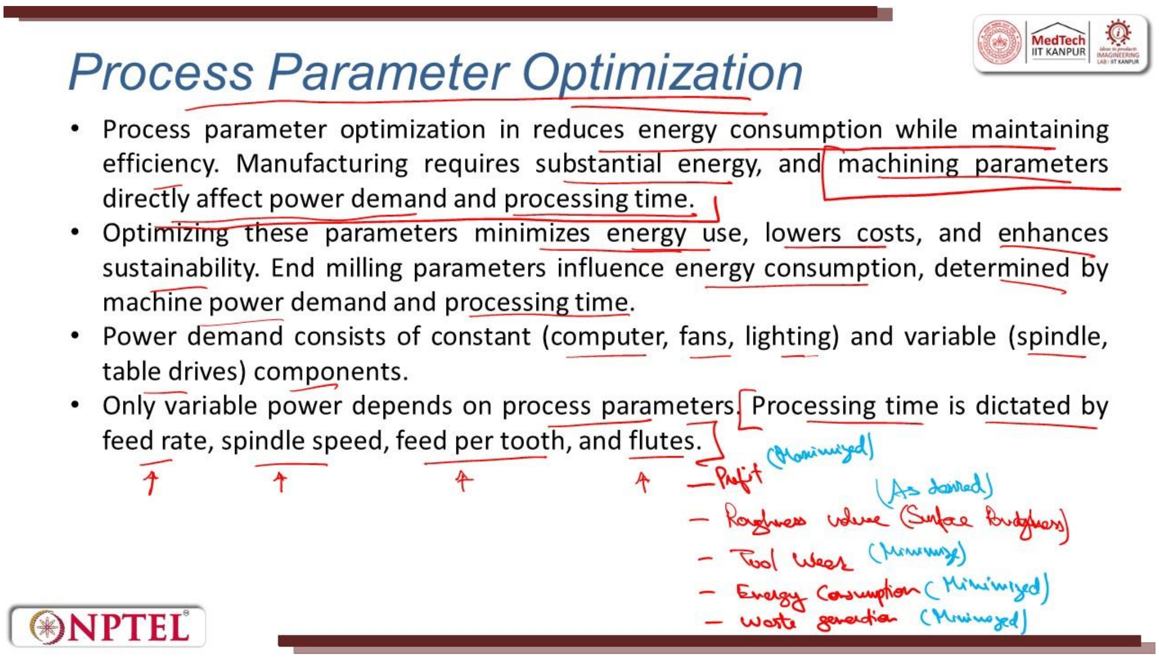
Next is magnetic assisted machining. When you use machining using magnetic assistance, the tool is magnetized specifically in reamers. The cutting edge is having longer tool life.

The reamers are magnetized and when magnetized reamer is used, reamers are the finishing materials. finishing for the finishing of the holes the remerge are used after drilling of the holes. So those are magnetized working principle is use a magnetic fields to control the movement of abrasive particles. Or machining tools reducing friction improving material removal efficiency. It enhances machining accuracy improves tool life enables non-contact machining.

For delicate components, the advantages are that it is ideal for precision machining, reduces tool wear, and provides a better surface finish. It also minimizes mechanical stress on the tool. The limitations are the requirement of special equipment when trying to use magnetic-resistant machining. It is also limited to materials with magnetic properties only. That is, only ferromagnetic materials are used, and it may not be effective for non-ferrous materials.

Applications include precision manufacturing of micro-components, biomedical implants, aerospace parts, and high-accuracy electronic components. In magnetic system machining, what is there? There is a workpiece and two magnets. This is the north pole, and this is the south pole. In between, we have magnetic abrasives.

This is MAF, that is, magnetic abrasive finishing, in which the tool and the base are magnetized. These abrasives are held in between, and the magnetic equipotential lines help control them in the confined area. Finishing occurs through this—this is the finished part, and this is unfinished.



Process parameter optimization, whatever kind of technologies we use Majorly, it will come down to, it boils down to the parameter optimization. If you are using a hybrid machining system. For example, if I am taking assistance of laser in electrochemical machining.

The parameters that what intensity of laser would be used, what would the voltage in electrochemical machining. What kind of the dielectric fluid I am using, all those are the parameters which would decide the final machining output which I need to do.

Some of the examples of the upper parameter optimization I will just discuss here and that is the most important part whatever we do. Process parameter optimization. Process parameter optimization reduces energy consumption while maintaining efficiency. Manufacturing requires substantial energy. Machining parameters directly affect power demand and processing time.

This is very important. Machining parameters directly affect power demand and processing time. Optimizing these parameters minimizes energy use, lower costs, enhances sustainability and billing parameters. Influence energy consumption determined by machine power demand and processing time. Power demand consists of constant that is computer fans lighting.

Which are our facilities in the manufacturing concern and there are variable costs. For example spindle table drives components in any of the system. There are variable and fixed cost example fan room lighting these are all kind of the permanent. Now while recording the camera is being used the camera energy being used in camera. That is a variable cost only variable power depends on the process parameter processing time is detected by the feed rate spindle speed.

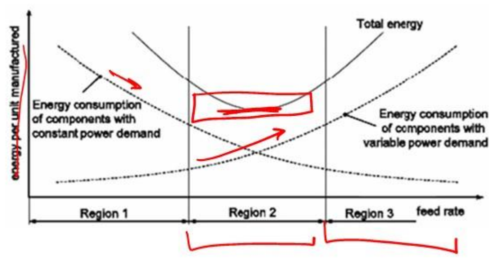
Feed per tooth and fluids this when we talk about machining these are parameters which determine our processing time. Process parameters it is to be optimized in a way feed rate is to be fixed to a specific level spindle speed feed per tooth and kind of the fluid chain drill. These are all the process parameters which are taken and the output or responses. Which determines what is the optimized value could be roughness value. Roughness value or I will call it at surface roughness.

Then tool where. When we are talking about sustainable engineering, I will take here also as energy consumption. As one of the parameters and waste generation. One of the parameters the roughness value is as desired depending upon the surface finish. Be required tool wear has to be minimum energy consumption has to be again minimized.

And waste generation also has to be minimized, and from the economic viewpoint, if I try to put it, there could be cost or, I would say, profit. Profit is to be maximized.

Process Parameter Optimization

- Higher feed rates reduce processing time but increase power demand. Three machining regions exist:
  - **Region 1**: Faster feed reduces energy per unit.
  - **Region 2**: Energy remains stable.
  - **Region 3**: Slower feed lowers energy.

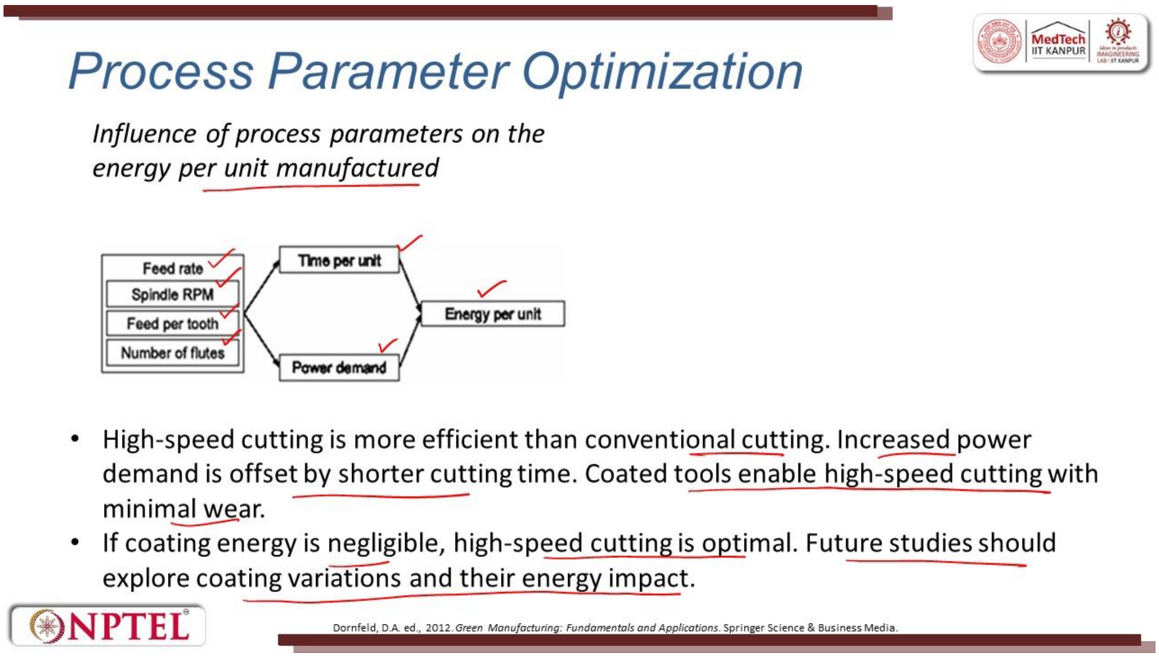


Dornfeld, D.A. ed., 2012. *Green Manufacturing: Fundamentals and Applications*. Springer Science & Business Media.

There is one example here, which is taken from a study given in this source. Higher feed rates reduce processing time but increase power demand. Three machining regions of the experiments taken by this researcher are region one, where faster feed reduces energy per unit.

You can see this is the energy consumption of a component with constant power demand. And this is the energy consumption of components with variable power demands. And this is the total energy. Region 1 is here, where faster feed reduces energy per unit. Region 3 is here, where slower feed lowers energy.

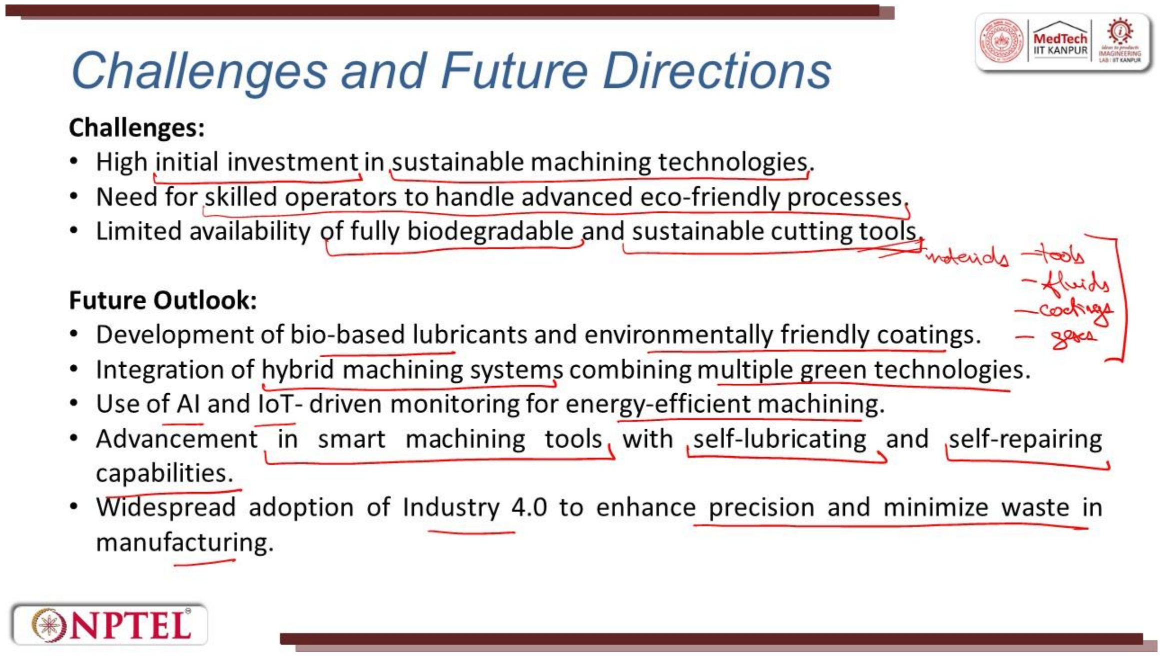
In between, we have region 2, where energy remains stable. So the lowest energy that is consumed is at this point here. So this is energy per unit manufactured.



In green machining, the influence of process parameters on the energy per unit manufactured. Parameters are feed rate, spindle RPM, feed per tooth, and number of fluids in case of drilling or reaming.

Time per unit and power demand are the factors which are taken and energy per unit is the response that is taken here. So high speed cutting is more efficient than conventional machine cutting. This was output taken from this study. Increased power demand is offset by shortening cutting time. Coated tools enable high-speed cutting with minimal wear.

If coating energy is negligible, high-speed cutting is optimal. Future studies should explore coating variations and their energy impact. That is, coated tools as is represented or presented in the previous slide is one of the techniques to have green machining in case of dry machining.



Challenges and future directions in sustainable or green machining strategies high initial investment is always there. Sustainable machining technologies are sought and high initial investment is there need for skilled operators.

To handle advanced eco-friendly processes is limited availability of fully biodegradable and sustainable cutting tools not even tools, i will say materials These materials could be tools, fluids, coatings, gases, etc. They are limited. Future outlook development of bio-based lubricants and environmentally friendly coatings are being developed. Integration of hybrid machining systems combining multiple green technologies is being developed.

The use of AI and IoT-driven monitoring for energy-efficient machining is there. But once mentioned, smart machining tools with self-lubricating and self-repairing capabilities are there. Widespread adoption of Industry 4.0 to enhance precision and minimize waste in manufacturing is there. With this, I am closing my lecture. I will talk about some green metrics in the next and the last lecture of this week and of this course.

Thank you.