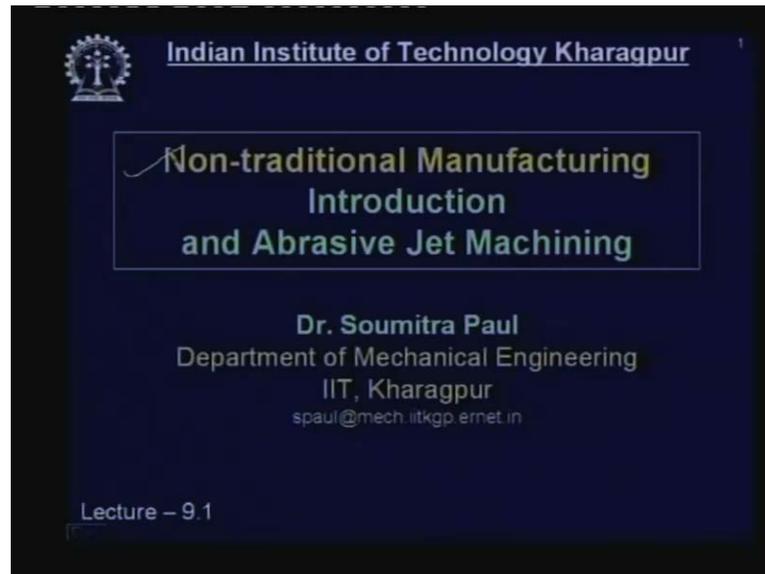


Manufacturing Processes II
Prof. S. Paul
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture No.35
Non-Traditional Manufacturing Introduction & Abrasive Jet Machining

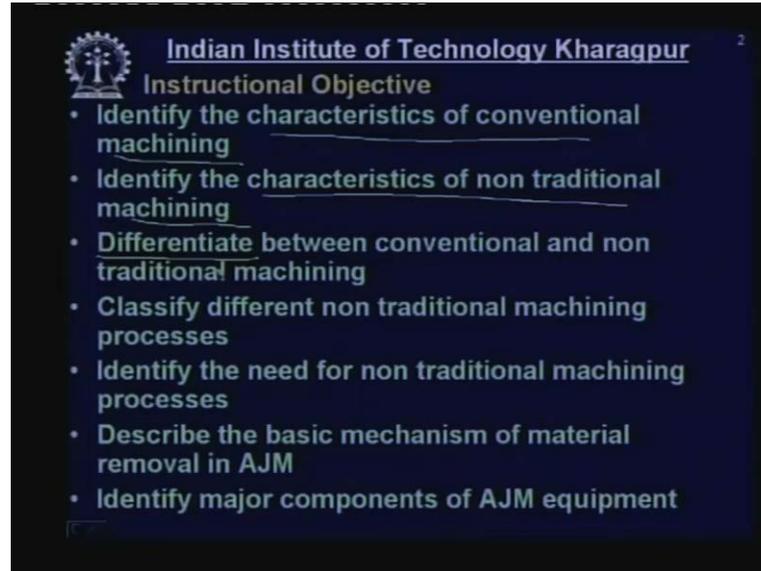
Good morning! Welcome to Manufacturing Processes lecture classes.

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Today we are going to start a new module, Module number-9 on Non-traditional Manufacturing. Today we are going to cover broadly two areas of Non-traditional Manufacturing. We are going to introduce the subject of Non-Traditional Manufacturing and after that we are going to take one manufacturing process within it which is abrasive jet machining. Before going in to the actual, let us identify the instructional objectives.

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The slide features the IIT Kharagpur logo on the left and the text 'Indian Institute of Technology Kharagpur' at the top right. Below the logo is the title 'Instructional Objective'. A list of seven objectives follows, each preceded by a bullet point. The first two objectives are underlined. A small number '2' is visible in the top right corner of the slide.

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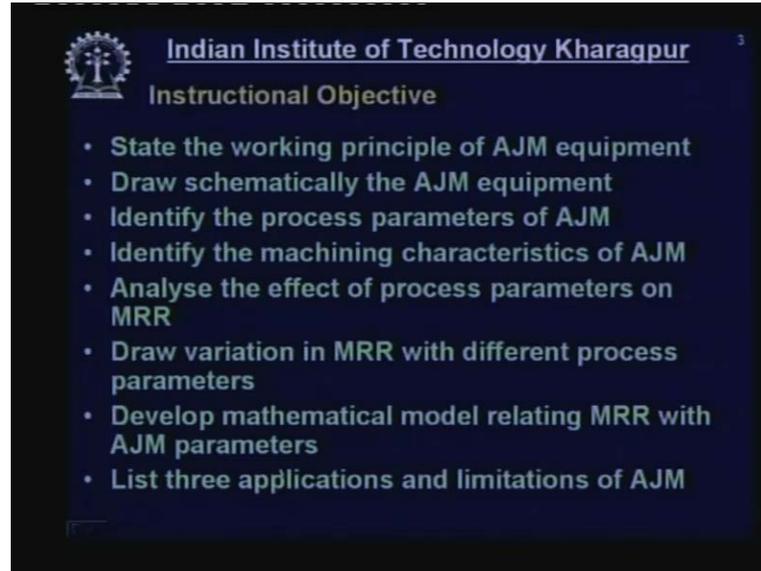
Instructional Objective

- Identify the characteristics of conventional machining
- Identify the characteristics of non traditional machining
- Differentiate between conventional and non traditional machining
- Classify different non traditional machining processes
- Identify the need for non traditional machining processes
- Describe the basic mechanism of material removal in AJM
- Identify major components of AJM equipment

What are instructional objectives? These basically says, what we are going to learn today. Today we are going to mainly identify the characteristics of different conventional machining process. Our lesson is non-traditional machining process. So first we need to know what are the characteristics of the other machining process namely conventional one. Once you have learnt that we are going to come to the characteristics of non-traditional machining general characteristics. Once these two have been achieved then we can differentiate between the conventional machining processes as well as non-traditional machining processes. Then, there are different types of non-traditional machining processes. So we need to understand classification of non-traditional machining processes as well.

However, conventional machining processes were there for edges and they were serving all the purpose. So why all of a sudden there was a need for non-traditional machining processes that also required to be studied. So these one two three four and five points basically deals with the introduction part. The other instructional objectives namely are on abrasive jet machining processes. First one is, we need to understand the basic mechanism of material removal of abrasive jet machining.

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The slide features the IIT Kharagpur logo on the left and the text 'Indian Institute of Technology Kharagpur' at the top right. Below the logo is the title 'Instructional Objective'. A bulleted list of seven objectives follows, detailing the goals for understanding AJM equipment, parameters, and characteristics.

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Instructional Objective

- State the working principle of AJM equipment
- Draw schematically the AJM equipment
- Identify the process parameters of AJM
- Identify the machining characteristics of AJM
- Analyse the effect of process parameters on MRR
- Draw variation in MRR with different process parameters
- Develop mathematical model relating MRR with AJM parameters
- List three applications and limitations of AJM

We need to understand the major components of abrasive jet machining equipments, their working principle. We should be able to draw the AJM equipment or abrasive jet machining equipment once you go through this particular lecture. We need to understand what are the process parameters of abrasive jet machining and what are the machining characteristics and analyze the effect of process parameters on one such machining characteristics which is material removal rate, draw variation in material removal rate which is the primary machining characteristics with different process parameters that means, if we can do that we would be able to understand, what is the effect of one process parameter on one of the most important machining characteristics namely material removal rate. We are also going to develop mathematical ball models relating material removal rate with respect to AJM parameters. Last but not the least, we need to understand the application areas of AJM and limitations of AJM. So first we will start with the basic classification of manufacturing processes all together.

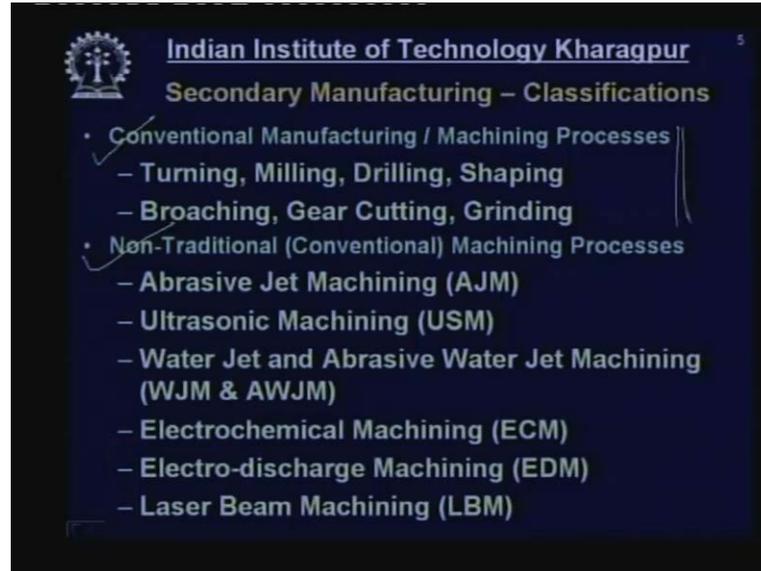
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As we all know, there could be primary manufacturing processes as well as secondary manufacturing processes. There are also other manufacturing processes which are tertiary manufacturing processes like coating new manufacturing processes like generative manufacturing or rapid prototyping but we are restricting our classification to only primary manufacturing and secondary manufacturing. So what is the need or purpose of primary manufacturing? The purpose of primary manufacturing is to impart basic shape and size to my material. It can be done in liquid state. It can be done in solid state as well as it can be done in powder state. In liquid state you all know the forming process. Any casting process, be die casting or green mold casting anything is a liquid state forming process.

One of the solid state forming processes conventionally what we know as the hot working or cold working processes or all metal working processes like forging, rolling, extrusions. They are solid state forming processes. Powder state forming processes are powder metallurgy the way cutting tool inserts are produced. Next comes the secondary manufacturing. So, how the secondary manufacturing processes are different from the primary manufacturing process? In primary manufacturing processes, we were giving or imparting basic shape and size. In the secondary manufacturing as well we are doing the same thing but there is a small difference what is that small difference? We are imparting the final shape and size with tight control on dimension and shape. This cannot be achieved by casting or rolling but this can very much achieved by secondary manufacturing processes. Most of the secondary manufacturing processes are material removal processes. So this is the basic classification of manufacturing processes. Now let us go in to the classification of secondary manufacturing processes. In today's course, manufacturing processes II, we are basically dealing with all secondary manufacturing processes.

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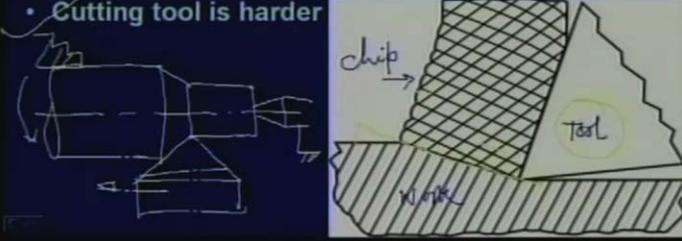
There are two major divisions. One is conventional manufacturing or machining processes and non-traditional machining processes. In other modules, non-conventional machining processes is being dealt with and today we are starting with non-traditional machining processes Module number 9. So you all know by this time what are the conventional machining processes? They are like turning, milling, drilling, grinding, shaping. So these are the conventional machining processes and what are the some of the non-traditional manufacturing processes? One of them is abrasive jet machining. What we are going to cover today? Ultrasonic machining which would be covering in the next class. Another one is water jet and abrasive water jet machining. This should also be covered in this module. Electrochemical Machining, Electro-discharge machining and Laser Beam Machining.

So these six processes are the representative processes of non-traditional machining. Here are other processes as well like plasma machining, ion beam machining, electron beam machining. We are not going to cover all of them in this particular module. These six representative processes would be covered in details. Now, let us try to understand the characteristics of conventional machining process.

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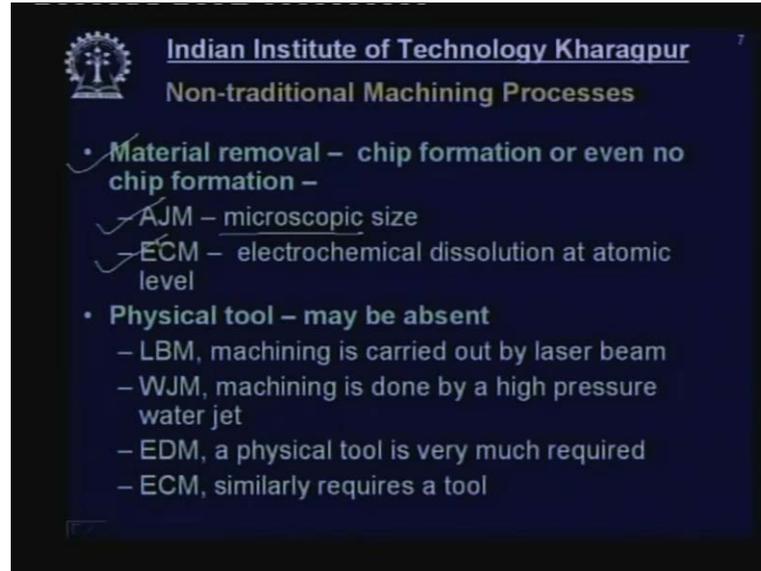
 Indian Institute of Technology Kharagpur
Conventional Machining Processes

- Material removal due to application of cutting forces
- Energy domain – mechanical
- Macroscopic chip
- Chip formation due to shear deformation
- Cutting tool is harder



So first let us draw a turning. So, this is my blank which is being turned. This is the chuck. This is my tailstock support. This is my tool, the job is getting giving a rotation and the tool is given a feed and this is the chip formation process which has been drawn here. This is my tool this is my work piece. **So this is my tool and this is my work piece** this is my chip. So here chip is being formed against the application of the cutting force. So what are the characteristics? There is a macroscopic chip. In conventional machining processes, there is a macroscopic chip formation. How are the chip formation takes place? It takes place due to shear deformation. These are the shear lines as you can see. This is the shear plane. This is my shear angle. There is a requirement of the cutting tool and the cutting tool needs to be harder than the work piece. Material removal takes place because of application of the cutting force. The force is being imparted on the tool because of the cutting process and the energy domain of conventional machining process is mechanical in nature. So these are the five major characteristics of conventional machining process. Now, let us see what are the characteristics of non-traditional machining processes?

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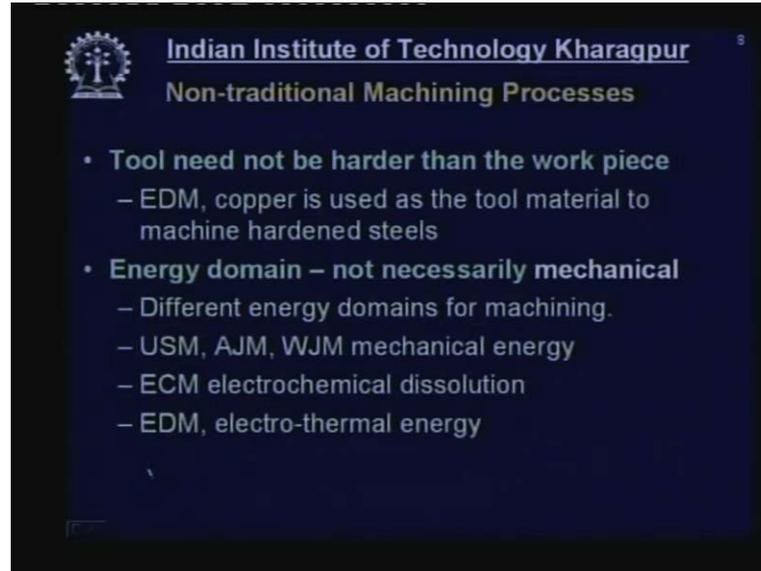
The slide features the IIT Kharagpur logo in the top left corner. The title 'Indian Institute of Technology Kharagpur' is at the top, followed by 'Non-traditional Machining Processes'. The content is organized into two main bullet points with sub-points. The first bullet point, 'Material removal – chip formation or even no chip formation –', includes sub-points for 'AJM – microscopic size' and 'ECM – electrochemical dissolution at atomic level'. The second bullet point, 'Physical tool – may be absent', includes sub-points for 'LBM, machining is carried out by laser beam', 'WJM, machining is done by a high pressure water jet', 'EDM, a physical tool is very much required', and 'ECM, similarly requires a tool'. A small number '7' is visible in the top right corner of the slide.

- **Material removal – chip formation or even no chip formation –**
 - AJM – microscopic size
 - ECM – electrochemical dissolution at atomic level
- **Physical tool – may be absent**
 - LBM, machining is carried out by laser beam
 - WJM, machining is done by a high pressure water jet
 - EDM, a physical tool is very much required
 - ECM, similarly requires a tool

In non-traditional machining processes, material removal takes place quite often with chip formation or even no chip formation may occur. Say for example in abrasive jet machining process, what we are going to cover today? Chip formation last take place but the chips are microscopic is size. They are not macroscopic in size as in turning or milling in another non-traditional machining process which should be covered later on. Electrochemical machining, machining occurs due to electrochemical dissolution at atomic level there is no microscopic chip formation even present.

Next comes the question of physical tool. In conventional machining process, I require a physical tool and it has to be harder than the work piece. But in non-traditional machining process a physical tool may as well as be totally absent. Say for example, in laser beam machining we are machining with the thermal energy source of a laser beam. There is absolutely no physical tool available there. In water jet machining process, machining is carried out by high pressure water jet. So it is a flexible tool. It is not a rigid physical tool. There is a water jet but it is flexible, in electro-discharge machining. However, there is a physical tool requirement. So physical tool may be absent. It is not necessarily always absent it may be absent. Similarly in electrochemical machining as well you require a physical tool. Now other characteristics are

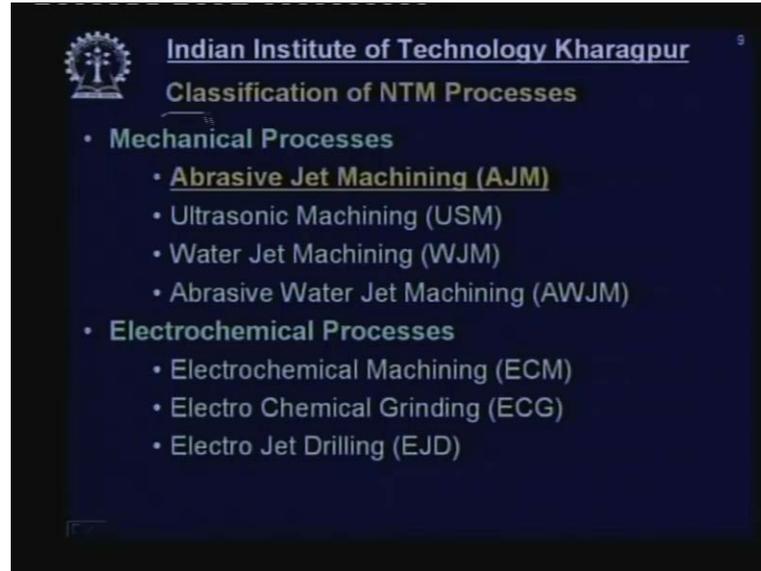
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One of the major characteristics of conventional machining process was tool has to be harder. In non-traditional machining processes tool need not be harder. It can be softer say for example in electro-discharge machining, one can machine very hard metallic alloys using copper as the tool material or graphite as the tool material. They are much more softer than the work piece which are being machined like hardened steel or inconel or titanium alloys. So in case of electro-discharge machining, tool need not be harder if a physical tool is present. Then comes the energy domain. Already, we have identified in mechanical in conventional machining the energy domain is purely mechanical where chip formation occurs due to shear deformation due to application of cutting force. But in non-traditional, it need not be necessarily mechanical it can be other as well. There are different energy domains available of machining.

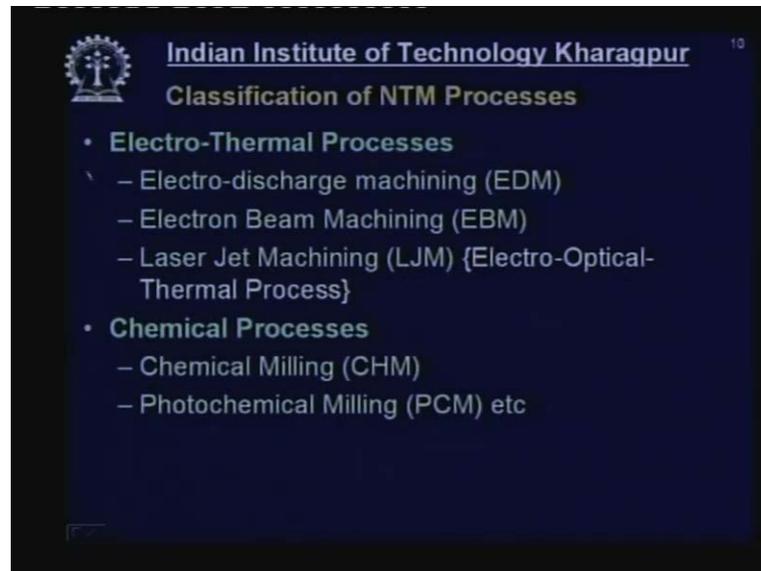
For example; Ultrasonic Machining, abrasive jet machining, water jet machining or even abrasive water jet machining. In all these, the energy domain is mechanical. However in electrochemical machining, it is due to electrochemical dissolution. In electro-discharge machining it is an electro-thermal machining process. So we conclude that energy domain can be mechanical or it can be other energy sources as well. So, these are the major characteristics of non-traditional machining processes. Now based on these characteristics once again we can classify different non-traditional machining processes what are they?

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Broadly it can be classified as mechanical processes where mechanical energy is used for material removal. We can classify it as electrochemical processes.

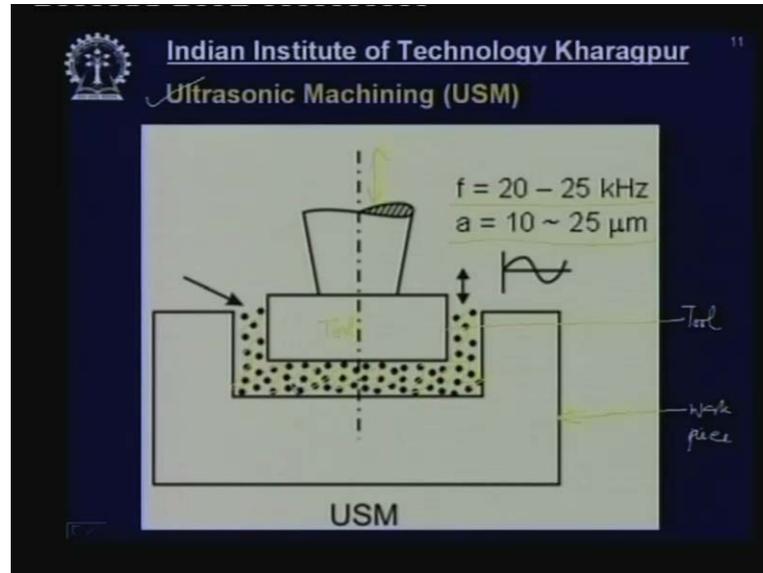
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We can classify it as electro-thermal processes as well as chemical processes. For chemical under chemical processes, what we have? We have chemical milling, photochemical milling. Photochemical milling is very much used in electronic industry under electro-thermal processes, we have Electro-discharge machining, Electron beam machining, Laser beam machining. So all these would be covered in the later classes. Now let us come to mechanic processes. Today we are going to abrasive jet machining. This is mechanical

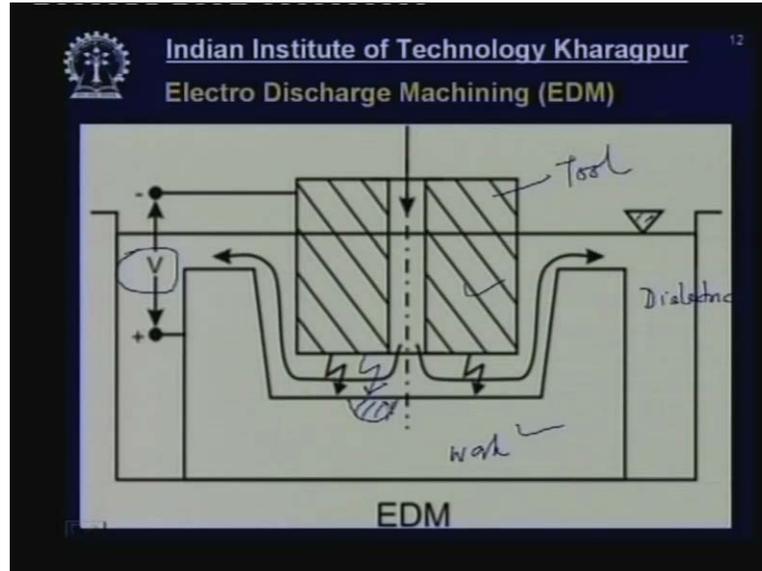
process where material removal occurs because of application of mechanical energy. Other processes are USM, WJM and abrasive water jet. Electrochemical machining processes are electrochemical machining, electrochemical grinding and electro jet drilling. So this is the basic classification of non-traditional machining process. Now before we go in to abrasive jet machining in detail manner, let us start upon different non-traditional machining processes. This is ultrasonic machining. What is it?

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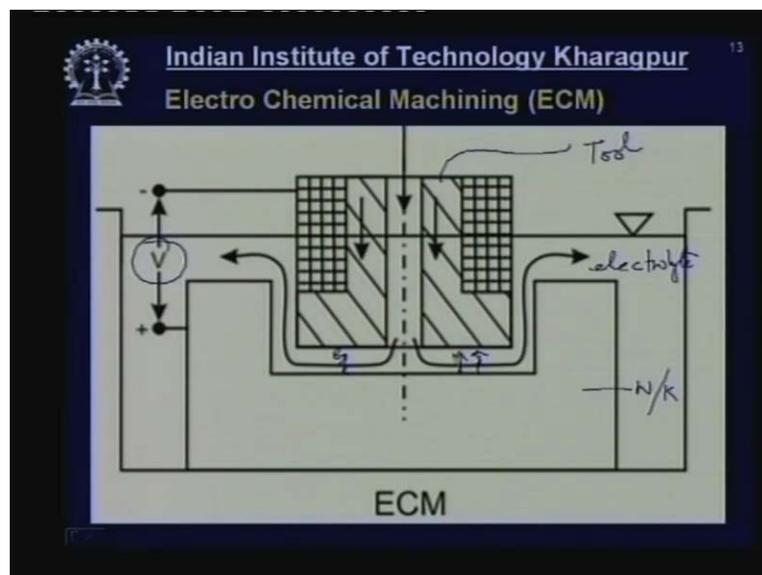
There is a tool in ultrasonic machining process. This is my tool, there is a work piece. This one is my work piece and this tool vibrates with an ultrasonic frequency. What is the nature of vibration? Ultrasonic the frequency of vibration is around 20 to 25 kilohertz and the amplitude of vibration is around 10 to 25 micron. When it vibrates between the tool and the work piece, this area is supplied with abrasive slurry. As the tool vibrates, the abrasive particles interact with the work piece. Most often brittle materials are machined. As these abrasive particles interacts with the work piece, it basically induces controlled fracture in the work piece and there by material removal takes place. Now let us come to another process which is electro-discharge machining process.

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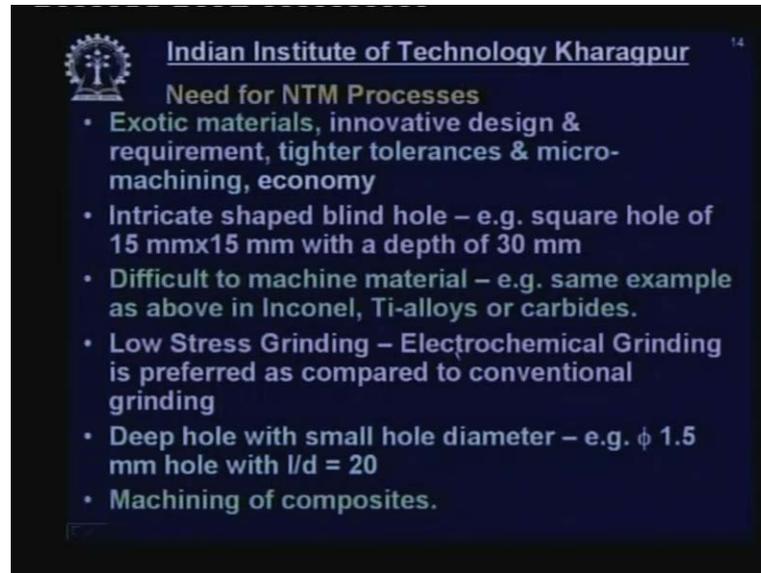
In electro-discharge machining process, we have already learnt what is the energy domain classification? It belongs to electro-thermal processes. Here, this is my tool. This is my work piece; between the tool and the work piece it is emerged in a dielectric medium and a potential difference is applied between the tool and the work piece **between my tool and the work piece a potential difference is applied**. As the potential difference is applied, the dielectric breaks down and there is a sparking. The thermal energy of the spark would melt some amount of material and gradually there would be material removal. So this is about electro-discharge machining. Now, let us come to electrochemical machining.

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Here material removal occurs because of electrochemical dissolution. Here also I have a tool and I have a work piece but it is not immersed in a dielectric medium. It is immersed in an electrolyte medium and a potential difference is once again applied between the tool and the work piece and because of electrochemical dissolution, there is no sparking because of electrochemical dissolution gradually the work piece is removed or material is removed. So energy domains are pretty different. Now, let us come to the need of non-traditional machining process.

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Need for NTM Processes

- Exotic materials, innovative design & requirement, tighter tolerances & micro-machining, economy
- Intricate shaped blind hole – e.g. square hole of 15 mmx15 mm with a depth of 30 mm
- Difficult to machine material – e.g. same example as above in Inconel, Ti-alloys or carbides.
- Low Stress Grinding – Electrochemical Grinding is preferred as compared to conventional grinding
- Deep hole with small hole diameter – e.g. ϕ 1.5 mm hole with $l/d = 20$
- Machining of composites.

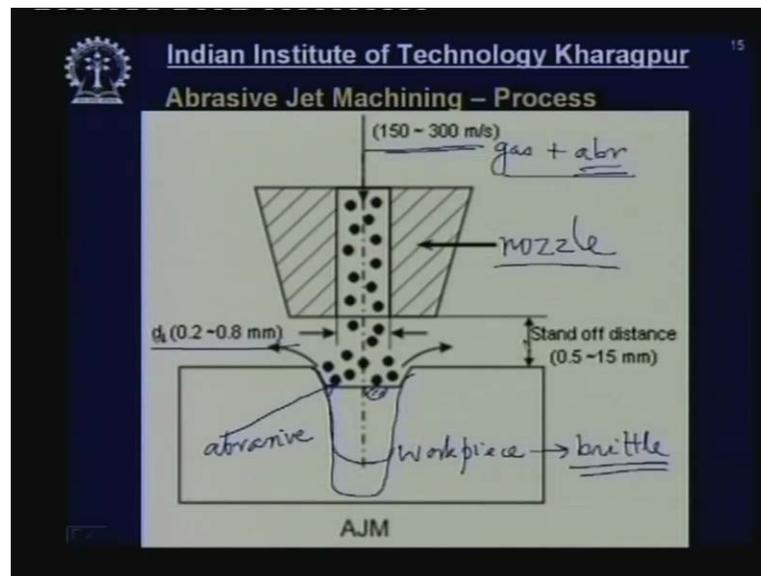
Conventional machining processes were there. They were providing the economic benefits manufacturability of different materials. However gradually there was lot of development in the material side. Lot of exotic materials were coming up which were not which could not be machined efficiently using conventional machining processes. So thus this was one need one requirement for which non-traditional machining processes were developed. Then there was innovative design and requirement tighter tolerances and micro-machining. So these are the new requirements of the new age which could not be made from the conventional machining root.

So a need or requirement was felt for development of non-traditional processes. Let us take some example. Say for example, you have to drill a blind hole. It is a square hole, drilling a square hole using conventional methods is very difficult. Moreover it is a blind hole having a dimension of 15 millimeter by 15 millimeter with a depth of 30 millimeter. Machining such a hole using conventional machining process is rather difficult. However, if one would like to machine it with electro-discharge machining, it is a very very easy solution. Now let us come to the material point of view. There are new materials which are very difficult to machine what are they? You have materials like Inconel; it is nickel super alloy you have titanium alloys, you have carbide ceramics. These materials are very difficult to machine and all the time one cannot develop cutting tools for conventional machining which are much harder than the tool material. So, if they can be machined in a way where

hardness does not come in to picture. Yes they can be machined inconel titanium they can very easily be machined using electrochemical machining and electro-discharge machining. Now even within conventional machining process, there where some requirements like low stress grinding.

Grinding is a finishing process as we all know, under conventional machining process. When we grind there may be induction or introduction of tensile residual stress. So, there is a requirement of low stress grinding. In conventional machining, if one if one has to do low stress grinding than he has to reduce the productivity which is not a very effective or efficient way of doing it but electrochemical grinding can provide almost stress free surface. Then there are requirements of machining of composite deep hole drilling and all of this. So gradually the need for non-traditional machining processes were getting established in the industry and nowadays they are very much there and non-traditional machining processes are as essentially as the conventional machining processes. One cannot fully replace the other one, but requirement of presence of both of them is very much required in machining industries. Now let us come to abrasive jet machining which is the second part of our lecture today.

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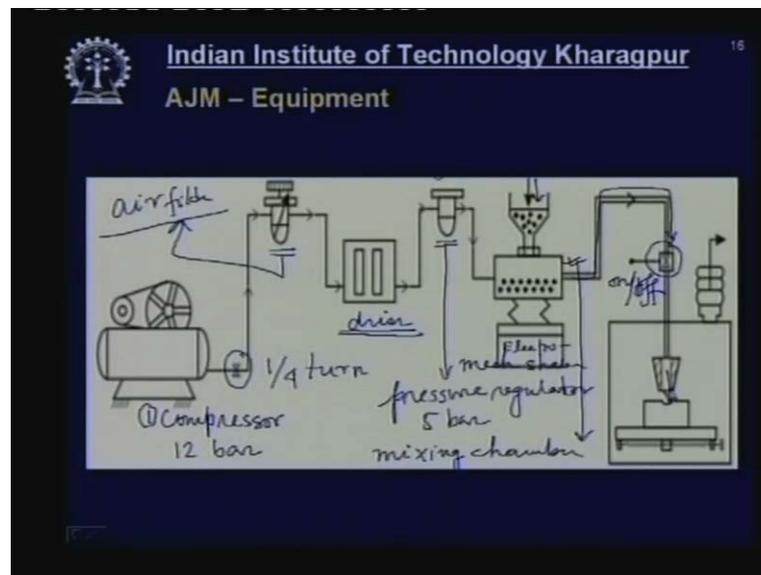


We are going to first study, how abrasive jet machining or what is the mechanism of material removal. What we have here? Here we have a nozzle. In this nozzle, there is an opening or a inner diameter which is typically around 0.2 to 0.8 millimeter. Through this nozzle a mixture of gas and abrasive particles are fed. They are fed at a velocity of 150 to 300 meter per second. These abrasive particles when they are issued from this particular nozzle they would interact with my work piece. Typically for abrasive jet machining brittle work piece brittle materials are machined more efficiently. So if you are using abrasive jet machining as a machining process you should rather try to machine glasses or other brittle materials rather than low carbon steel. Once this abrasive particles, these are my individual

abrasive particles when they interact with the work piece, they have some amount of kinetic energy.

As they interact with the work piece that kinetic energy is converted in to mechanical work. They would intend the surface. They would create a small crater and the kinetic energy would be absorbed with the work done. For producing this particular crater and in this way with multiple impact gradually we will be getting a machining. So this is a pure mechanical domain process where the mechanical energy of a high speed abrasive **high speed abrasive** is used for machining the material and the machining occurs because of the brittle fracture of the work piece. Now, let us come to the general description of abrasive jet machining equipment what we require?

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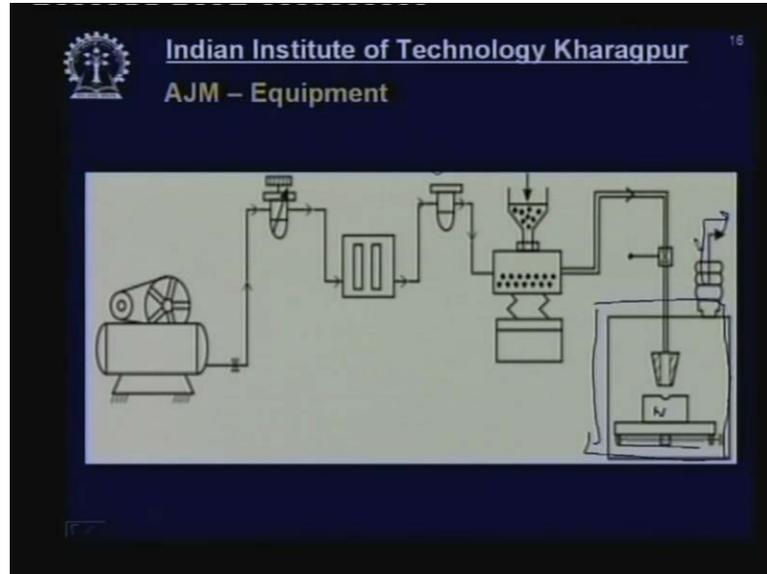


This is the first requirement which is my compressor because I require a gas. This compressor is fed through the line through a valve. This is typically a quarter turn valve. Then, you have this piece of equipment what is this? This is an air filter. Whatever air is coming out of the compressor oil and moisture is removed. This is drier this is a moisture separator or a drier this can be a regenerative drier or it can be other kind of drier as well. Here you have a pressure regulator say for example, your compressor is issuing air at twelve bar and your working pressure is five bar. So this pressure regulator would be reducing or giving you a regulated supply.

After the pressure regulator it goes in to this particular chamber, this chamber is known as the mixing chamber. Within the mixing chamber, abrasive is fed from the top through a hopper and this is an electromechanical shaker. So with this the mixing chamber is always being violently vibrated. So that there is proper mixing of this air or the carrier gas and the abrasive particles. Once they have mixed together then they are fed through a line like this and here you have a pneumatic electro pneumatic valve on off type valve. This is not a quarter turn valve this is on off type valve. So when the valve is on, the abrasive and the gas

mixture is allowed to issue from the nozzle which we have all ready discussed in the previous slide. It is allowed to issue from the nozzle which is which has been shown here.

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This is your work piece and this is the table with the lead screw. So that the work piece can be moved below the nozzle and the whole thing is there in an enclosed chamber because as the abrasive particles interact with your work piece, they will generate lot of dust. So it has to be properly taken care of. It cannot be simply taken out in the atmosphere there has to be proper exhaust system. So that the abrasive and the material, which is being removed can be separated properly before releasing the air in the atmosphere. Now let us come to the process variables which affect my abrasive jet machining process.

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The slide is a presentation slide from the Indian Institute of Technology Kharagpur. It features the institute's logo in the top left corner and the text 'Indian Institute of Technology Kharagpur' in the top right. The main title is 'Process Variables'. Below this, there are two main categories: 'Abrasive' and 'Carrier gas'. Under 'Abrasive', the variables listed are: Material (Al₂O₃ / SiC / glass beads), Shape (irregular / spherical), Size (10 ~ 50 μm), and Mass flow rate (2 ~ 20 gm/min). Under 'Carrier gas', the variables listed are: Composition (Air, CO₂, N₂), Density (Air ~ 1.3 kg/m³), Velocity (500 ~ 700 m/s), Pressure (2 ~ 10 bar), and Flow Rate (5 ~ 30 lpm). There are handwritten checkmarks and arrows next to the Velocity, Pressure, and Flow Rate items.

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Process Variables

- **Abrasive**
 - Material – Al₂O₃ / SiC / glass beads
 - Shape – irregular / spherical
 - Size – 10 ~ 50 μm
 - Mass flow rate – 2 ~ 20 gm/min
- **Carrier gas**
 - Composition – Air, CO₂, N₂
 - Density – Air ~ 1.3 kg/m³
 - Velocity – 500 ~ 700 m/s
 - Pressure – 2 ~ 10 bar
 - Flow Rate – 5 ~ 30 lpm

What are the processes? What could be the process variables? I require abrasive so I need to classify what are the how this this this should be definitely be a major process variable. What would be the material of the abrasive? Generally aluminum oxide and silicon carbide is used quite often glass beads are also used then comes the shape of the abrasive. Once you are you have decided that you are going to use aluminum oxide or silicon carbide typically there shape is irregular but they are rather sharp. If someone is interested in using glass beads, there shape would be typically spherical. Now once you have decided about the material and the shape then comes what would be the size. Size of these abrasive particles are rather less they are in the range of ten to fifty micron then how much abrasive particle should I use that is the mass flow rate.

Typically the mass flow rate of abrasive particles is around 2 to 20 grams per minute. So they are also consumption rate of abrasive is rather less. Now, as we have discussed we require a gas to propel those abrasive particles. So other than this abrasive particles this carrier gas would also play an important role. Generally air can be used or else carbon dioxide or nitrogen can be used. Then we do not require if you are using carbon dioxide or nitrogen, then you do not require this compressor. Instead of that, you will issue the gas from a gas cylinder. So instead of the compressor you will issue it from the gas cylinder that is also possible.

So as a carrier gas typically air carbon dioxide and nitrogen is used. Typical density of the air is something around this. Velocity of the gas is around 500 to 700 meter per second. Pressure is around ten. Bar flow rate is around three to five to thirty lpm. One of the most important parameter is the pressure of this gas carrier gas because depending on the pressure, we will be getting a particular velocity and that will decide to what extent my abrasive particles would be or the abrasive jet would be abrasive particles should be accelerated.

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The slide is a presentation slide from the Indian Institute of Technology Kharagpur. It features the institute's logo in the top left corner and the text 'Indian Institute of Technology Kharagpur' in the top right. The main title is 'Process Variables'. Below this, there are two main bullet points: 'Abrasive Jet' and 'Nozzle'. Under 'Abrasive Jet', there are four sub-bullets: 'Velocity - 100 ~ 300 m/s', 'Mixing ratio - mass flow ratio of abrasive to gas', 'Stand-off distance - 0.5 ~ 5 mm', and 'Impingement Angle - 60° ~ 90°'. Under 'Nozzle', there are three sub-bullets: 'Material - WC / sapphire', 'Diameter - (Internal) 0.2 ~ 0.8 mm', and 'Life - 10 ~ 300 hours'. The text '18' is visible in the top right corner of the slide.

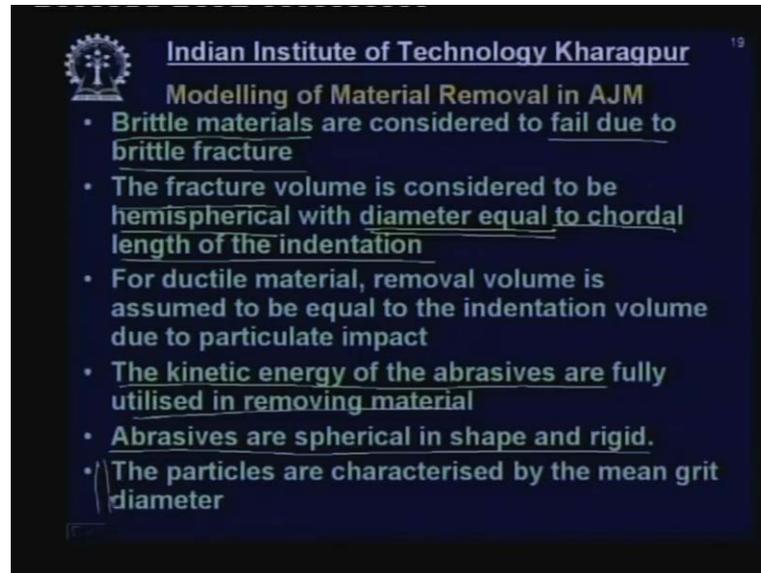
So once abrasive and the carrier gas they have mixed together, we will get the abrasive jet. How do I classify or identify the parameters of the abrasive jet? One is once again the velocity. The velocity is around 100 to 300 meter per second. If you go back one slide, you can see velocity of the carrier gas is five hundred to seven hundred, but this is hundred to three hundred. Why this drop? because once the abrasive particles are mixing with the carrier gas. The carrier gas would lose momentum and will gradually transfer its momentum to the abrasive jet. So that the abrasives can be accelerated and in the process your velocity will drop down than there is mixing ratio.

What is mixing ratio? How much abrasive you are pumping in to the system as compared to the mass flow rate of the gas. If you are pumping too much abrasive, they would not be accelerated properly. So mixing ratio is once again a very very important parameter then stand-off distance. How far is your nozzle from the jet from the work piece. This is your work piece. This is the end of the nozzle. So this is your stand-off distance. Typical stand-off distance is around in millimeters, then comes the impingement angle. At what angle the jet is interacting with the work piece? If there is no technical or geometrical requirement typically impingement angle is around 90 degree but it can also be as less as 60 degree, then comes the nozzle material because this nozzle material has to be such it is handling abrasive particles which are moving through the nozzle at 300 meter per second.

So we need to understand the requirement and the requirement is, it has to be wear resistant. Typically tungsten carbide nozzles are used or even wear resistance sapphire nozzles are used. The inner nozzles are characterized by their internal diameter and the internal diameter of the nozzle would be 0.2 to 0.8 millimeter. Why they have to be wear resistance? If they are not wear resistance, then you will not get good life from the nozzle quite often under industrial situation the life expected around hundred hours or ten hours. If you are getting ten minutes by using steel nozzles, then all the time you would be changing your nozzle there would be no production. So appreciable life of the nozzle is very very important for

which we require a wear resistance nozzle material. Now let us go in to gradually the modeling of material removal in abrasive jet machining process.

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Modelling of Material Removal in AJM

- Brittle materials are considered to fail due to brittle fracture
- The fracture volume is considered to be hemispherical with diameter equal to chordal length of the indentation
- For ductile material, removal volume is assumed to be equal to the indentation volume due to particulate impact
- The kinetic energy of the abrasives are fully utilised in removing material
- Abrasives are spherical in shape and rigid.
- The particles are characterised by the mean grit diameter

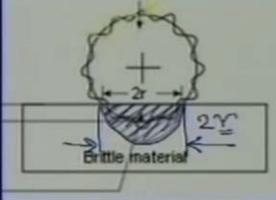
Today we are going to model only for brittle materials and it would be considered as those abrasive particles interact with the work piece. The material removal occurs due to brittle fracture. There is another consideration. Once a single abrasive particle interacts with the brittle material there would be a fracture and this fracture we be assume to be hemispherical and the diameter of the fracture would be the chordal length of the indentation. As the abrasive particle interacts with the work piece, it will create a small crater. That crater would be created because abrasive particles are highly kinetic energetic.

So the kinetic energy of the abrasive particle would be absorbed as it creates that crater and the diameter of that particular crater or indentation would be equal to the chordal length. Another assumption is kinetic energy of the abrasive particles would be considered to be fully utilized. It is not partial; whatever is the kinetic energy we will assume that total kinetic energy is utilized in doing the work done. Further, abrasive particles would be assumed to be rigid. They would be assumed not to disintegrate and they would be spherical in shape and the particle size would be characterized by the mean diameter. Now, let us come to the modeling part of it. Modeling of material removal rate in abrasive jet particle.

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Indian Institute of Technology Kharagpur
29

Modelling of MRR in AJM



Brittle material

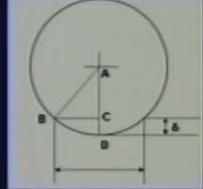
$$AB^2 = AC^2 + BC^2$$

$$BC^2 = r^2 = AB^2 - AC^2$$

$$r^2 = \left(\frac{d_g}{2}\right)^2 - \left\{\frac{d_g}{2} - \delta\right\}^2$$

$$r^2 = -\delta^2 + d_g\delta \cong d_g\delta$$

$$r = \sqrt{d_g\delta}$$



We were always seeing one abrasive particle. So, this is one small abrasive particle. Abrasives particles are not completely spherical. There are small undulations. However we are assuming it to be spherical. What else we are assuming? We are also assuming when it interacts with my material, it creates a hemispherical fracture and that hemispherical fracture is identified or indentation is identified by this chordal distance $2r$. Now we need to find out how much is this value of this r ? How we can find it out? Let us look in to the equations. First it says AB square. This particle distance hypotenuse is equal to AC square plus BC square. By rearranging I can write BC square which is nothing but the small r is AB square minus AC square. AB is nothing but the radius of the grit and AC is nothing but the radius of the grit minus δ .

What is that δ ? That δ is the indentation. So, assuming this δ to be very very less. It would be very less I can get an expression of the radius of my indentation which is root over grain diameter or grid diameter in to indentation. This particular relation will be very useful in finding out the material removal rate. Once I have this r , I can also find out how much is the amount of material removal in a single impact how much is my material removal, single impact material removal is this hemisphere. So what is the volume of my hemisphere?

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Indian Institute of Technology Kharagpur
Modelling of MRR in AJM

$$\Gamma_B = \frac{2}{3} \pi r^3 = \frac{2\pi}{3} (d_g \delta)^{3/2}$$

$$K.E._g = \frac{1}{2} m_g v^2 = \frac{1}{2} \left\{ \frac{\pi}{6} d_g^3 \rho_g \right\} v^2 = \frac{\pi}{12} d_g^3 \rho_g v^2$$

$$W = \frac{1}{2} F \delta \quad \begin{array}{l} F = \text{indentation area} \times \text{hardness} \\ F = \pi r^2 H \end{array}$$

$$\therefore W = \frac{1}{2} F \delta = \frac{1}{2} \pi r^2 H \delta$$

Volume of my hemisphere is two third pi r cube where 'r' is nothing but the radius of that indentation. Already we had an expression for 'r'. So I can put that expression here to get a expression for amount of volume of material removal in a single impact. Now let us try to see what is the kinetic energy of a grain or a particular abrasive particle? Kinetic energy of a particular abrasive particle is half mv square. 'm' is nothing but its volume in to its density. So this is my final expression of my kinetic energy. Now where is this kinetic energy expanded? This kinetic energy is expanded in doing the amount of work. So I need to write down equation or derive equations for finding out how much work is being done. When it is indenting the abrasive particles when it is gradually going inside the work piece, initially my force is zero and this force is increasing to a value of F.

How can I estimate this F? This F is indentation area in to hardness of the work piece that is a good estimation, so work done is half F in to delta. Why is it half F in to delta? Because 'F' was varying from zero to 'F'. It was not constant all the time. So now I have a relation for the total work done for doing an indentation which is half F in to delta which is nothing but half pi r square in to H. H is the hardness in to delta. So we have two terms; one is the work done another one is that of the kinetic energy and we where seeing the total kinetic energy is converted. So we can equate them to get some more expressions. So we are equating the total work to the kinetic energy.

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Modelling of MRR in AJM

W = K.E.

$$\frac{1}{2} \pi r^2 \delta H = \frac{\pi}{12} d_g^3 \rho_g v^2$$

$$\delta = \frac{d_g^3 \rho_g v^2}{6r^2 H} \quad \text{now } r = \sqrt{d_g \delta} \Rightarrow r^2 = d_g \delta$$

$$\delta^2 = \frac{d_g^2 \rho_g v^2}{6H}$$

$$\delta = d_g \left(v \left(\frac{\rho_g}{6H} \right)^{1/2} \right)$$

There is an assumption. The assumption is the whole of kinetic energy is converted and then once you equate it, we can find out the value of delta which is the indentation depth and this is the final expression for delta and delta seems to vary with 'dg'. As you increase dg you would have more indentation it seems to vary with velocity. If your particles are much more energetic definitely, your indentation would be higher. If the hardness of the work material is more, the indentation would definitely be less. So this particular expression looks physically very viable. Now, let us come to the material removal rate. How much would be my material removal rate?

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Modelling of MRR in AJM

$$MRR_B = \Gamma_B N$$

$$MRR_B = \Gamma_B \frac{m_a}{\text{mass of a grit}} = \frac{m_a}{\frac{\pi}{6} d_g^3 \rho_g} = \frac{6 \Gamma_B m_a}{\pi d_g^3 \rho_g} \quad \text{as } \Gamma_B = \frac{2\pi}{3} (d_g \delta)^{3/2}$$

$$= \frac{6 \times \frac{2\pi}{3} (d_g \delta)^{3/2} m_a}{\pi d_g^3 \rho_g} = \frac{4 m_a}{\rho_g} \left(\frac{\delta}{d_g} \right)^{3/2}$$

Material removal rate would be amount of material removed, this gamma B in a single impact in to number of impact. So that is what we have written. Amount of material removed in a single impact in to number of impacts. So it is very simple. How can we estimate number of impacts? Number of impacts can be very easily estimated. If I know what is my mass flow rate of the abrasive divided by mass of a single grit. So mass flow rate of the abrasive would be set on the machine and this is mass of a single grit. So once again one can get material removal rate in case of a brittle material as this particular expression which is written here in a better manner.

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Modelling of MRR in AJM

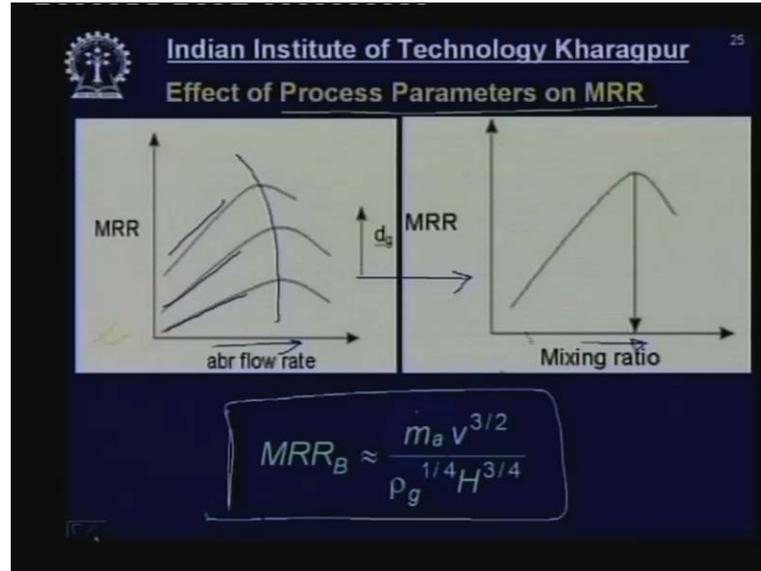
$$MRR_B = \frac{4m_a}{\rho_g} \left(\frac{\delta}{d_g} \right)^{3/2} \quad \text{as } \delta = d_g v \left(\frac{\rho_g}{6H} \right)^{1/2}$$

$$MRR_B = \frac{4m_a}{\rho_g} \cdot \left(\frac{d_g v}{d_g} \right)^{3/2} \left(\frac{\rho_g}{6H} \right)^{3/4}$$

$$MRR_B = \frac{4m_a v^{3/2}}{6^{3/4} \rho_g^{1/4} H^{3/4}} \quad \left[\frac{m_a v^{3/2}}{\rho_g^{1/4} H^{3/4}} \right]$$

So this was the expression. In that delta the indentation depth is still unknown. So we have already determined the value of the indentation depth. So now we are going to put that in this particular equation. To modify the material removal rate expression and the modified material, so this delta is being replaced with this expression and we get a modified material removal rate expression of this. How is it related? If we increase abrasive flow rate material removal rate is expected to increase. If we increase the velocity, the kinetic energy is increasing. So material removal rate is expected to increase. If you are using harder material harder work material definitely it would be much difficult to machine some material removal rate would go down. Now let us we have already identified all the process parameters. We have identified one of the major machining characteristics which is material removal rate. We have also modeled. Just now we have modeled **we have modeled** the material removal rate as well. Now let us see the effect of process parameters on material removal rate.

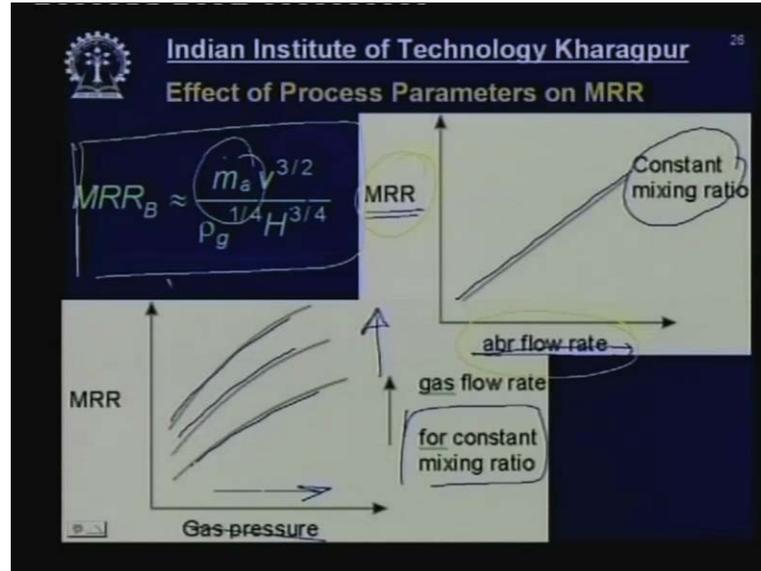
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This is my modeled information and these are actual experimental. These are actual experimental observations. So what we see here? We see as we increase abrasive flow rate, material removal rate increases. This is a good observation and it matches with my modeled value but there is a deviation. What is that deviation? After a particular material abrasive flow rate, there is a reduction. Why is this reduction? That can be explained very easily from this particular graph. How can we explain this one? This is mixing ratio. What is mixing ratio? Mixing ratio is the ratio of abrasive flow rate divided by gas flow rate.

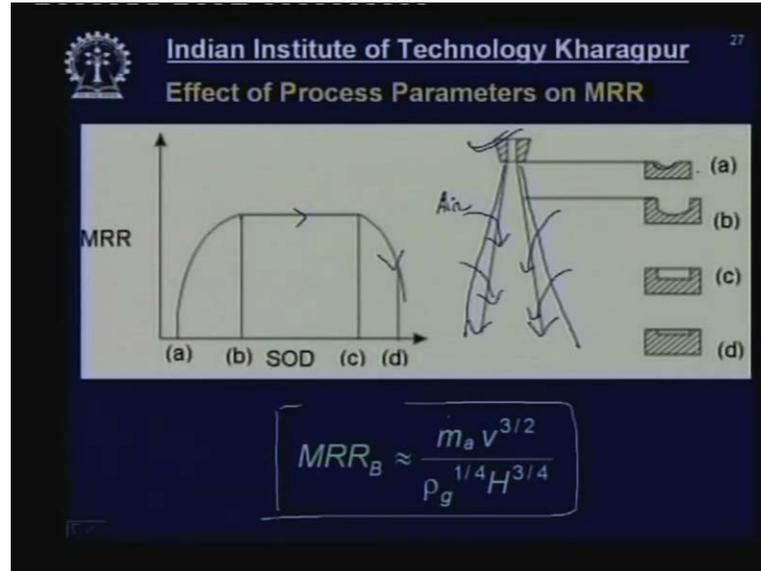
As we go on increasing, the mixing ratio we are putting in more abrasive particles. So definitely material removal rate is going up, but beyond a particular point there are so many abrasive particles. Gas does not have enough momentum. To accelerate them, so no longer there is benefit. There is a reduction in material removal rate. A similar model would be done under abrasive jet machining process that is another abrasive water jet machining process. A similar model would be done so at that moment of time, it would be very clear to why this phenomenon occurs. Now let us try to see the effect of gas pressure. **Let us try to see the effect of gas pressure** on material removal rate.

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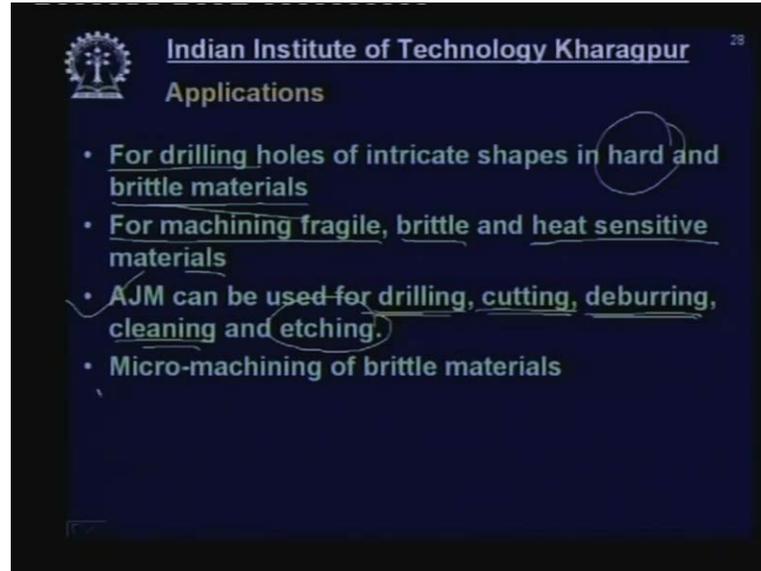
Once again, this is my modeled equation which says if you increase velocity, if you increase velocity, your material removal rate is going to increase as well. How do I increase velocity? With increasing gas pressure, this velocity is going to increase so the material removal rate is also going to increase. As you increase the gas flow rate, you can pump in more abrasives so you have different grams. As the gas flow rate increasing for a constant mixing ratio you material removal rate you get is more. This is material removal rate by abrasive flow rate. This is a constant straight line there is a catch. What is the catch? When I am increasing the abrasive flow rate I am also increasing the gas flow rate so that I get a constant mixing process. So whatever equation we have developed here, it is very true. **Whatever equation we have developed here it is very true** provided my mixing ratio is constant, if mixing ratio is constant material removal rate changes material removal rate changes with abrasive flow rate linearly as we have modeled. Now let us come to the effect of process parameters on material removal rate. This is another effect which is the stand of distance.

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The model that we have developed **the model that we have developed** in that there is no effect of stand of distance but it is there in an implied form. What is that implied form? This is my nozzle the small piece is my nozzle and it is issuing the jet. As the jet is being issued this jet is interacting with the air molecules around it is submerged jet. It is air jet within the air. So it will entrap air from the atmosphere and as it entraps air, there would be flaring of the jet, the jet would be very straight as it is being issued but after a length typically around ten internal diameter of the nozzle it will start flaring out. So, if your work piece is very near to the nozzle, you get a shape like this where the material removal is not much because the after interaction they cannot remove. If they are within appreciable distance material removal rate is very high till c more or less it is constant, then once again it drops down because as it flares out the energy of the particle is lost as it interacts with the air molecules present in the atmosphere. So this though has not been included in our model but it is very much there in an implied form. Now let us come to the applications of abrasive jet machining process.

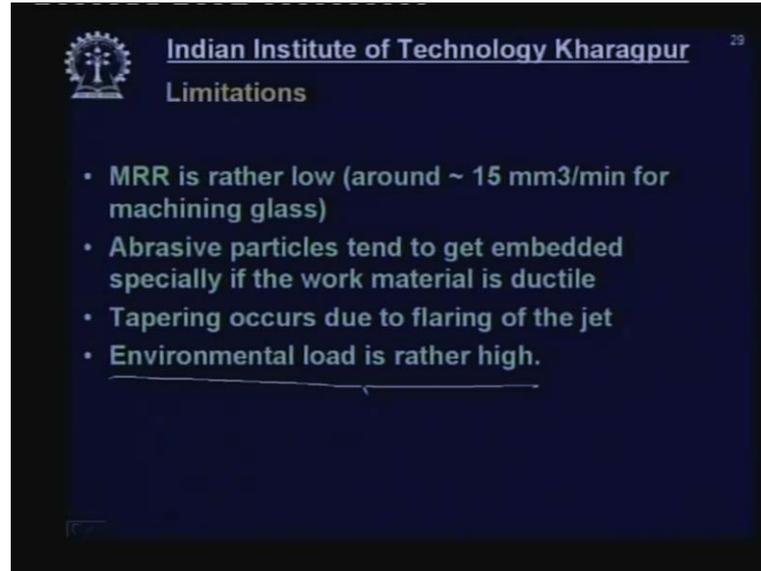
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Already we have said that abrasive jet machining. In abrasive machining jet machining, material is removed due to interaction of the high energy abrasive, high velocity abrasive particles with the material and as it interacts it creates small indentation or creates and those craters are formed because of the brittle fracture of the material. So, typically brittle materials are machined using abrasive jet machining and they are machined for drilling holes of intricate shapes and as because it is brittle material quite often those materials are also hard. In abrasive jet machining there is not much of cutting force.

Thus it can also be used for machining fragile objects, heat sensitive materials because there is no thermal damage or very less thermal damage and as well as brittle materials AJM can be used in different modes. It can be used for drilling operation. It can be used for deburring operation. It can be used for etching operation, it can also be used for cutting or slitting operation and there is another interesting application which is mechanical etching. Abrasive jet machining is not only finding application in conventional. In non-traditional machining of large dimensions they are all also finding application in micro-machining of brittle objects. However any process would have its advantages and some limitations. So let us look in to the limitations of abrasive jet machining process.

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The slide features the IIT Kharagpur logo in the top left corner. The title 'Indian Institute of Technology Kharagpur' is at the top center, with the slide number '29' in the top right. Below the title is the section header 'Limitations'. A list of four bullet points is centered on the slide, with a horizontal line underlining the last point.

- MRR is rather low (around ~ 15 mm³/min for machining glass)
- Abrasive particles tend to get embedded specially if the work material is ductile
- Tapering occurs due to flaring of the jet
- Environmental load is rather high.

Material removal rate in abrasive jet machining process is rather low. In conventional machining process or other non-traditional machining process, material removal rate can be very very high. But here, material removal rate is around 15 millimeter cube per meter. So which is not much there is another problem, abrasive particles quite often gets embedded in your work piece. If they get embedded in your work piece it is contamination of the work piece. So in certain applications, you cannot use them. In any jet manufacturing process be it abrasive jet abrasive water jet or water jet or even laser beam machining, there would be some amount of tapering due to flaring of the jet. As the jet flares out, it would loss energy and there would be tapering and as we have said earlier environmental problem is a problem in abrasive jet machining. In abrasive jet machining it has to be done in a enclosed environment and after machining lot of dust would be generated. So they cannot be simply thrown out. So in abrasive jet machining process, there is lot of load on the environment and which has to be taken care of. Otherwise you would be polluting the environment unnecessarily. Now let us come to the quiz part of it.

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Quiz

1. AJM nozzles are made of

- low carbon steel
- HSS
- WC
- Stainless steel

Al_2O_3/SiC
 $\sim 300 \text{ m/s}$

2. Material removal in AJM of glass is around

- 0.1 mm³/min
- 15 mm³/min
- 15 mm³/s
- 1500 mm³/min

These there are four questions under quiz and this basically tries to give you a flare of the subject what you have learnt today. Abrasive jet nozzles are made of? low carbon steel, is it made of HSS, is it made of tungsten carbide or stainless steel. The answer is tungsten carbide. But knowing the answer is not enough you need to know why it is correct? We all know in abrasive jet machining, nozzles are handling high velocity abrasives. What are those abrasives? The abrasives are aluminum oxide Al_2O_3 silicon carbide. They are abrasive particles. What is their velocity? Their velocity is around 300 meter per second. The velocity is rather high, at such a high velocity when these abrasive particles are moving through the nozzle if the nozzle is not wear resistance it is going to give you a very poor quality tool life that means it will wear out so fast you have to change the nozzle quit often. So you should use a very wear resistance material for building the nozzle. Out of the listed materials here, tungsten carbide is the most wear resistant material, low carbon steel even HSS cannot provide such amount of wear resistant. So this is your proper answer.

Now let us go to the next question. Material removal rate in abrasive jet machining **in abrasive jet machining** of glass is around 0.1 millimeter cube per minute 15 millimeter cube per minute 15 millimeter cube per second or fifteen thousand millimeter cube per minute. Basically here there is a change of order of at least six times. This option and this option and this option there is a change of order of two because this is almost hundred time less. Here also it is multiplied by sixty. Here also, there is a change of order of hundred from this place. So which one is correct? We all know one of the major limitations if you go back limitation of abrasive jet machining is material removal rate is rather low. But, it also not as low as this. So the appropriate answer is fifteen millimeter cube per minute. Now let us go to the second quiz second page.

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Indian Institute of Technology Kharagpur 31

Quiz

3. Material removal takes place in AJM due to

- electrochemical action
- mechanical impact
- fatigue failure of the material
- sparking on impact

4. As the stand off distance increases beyond 5 mm, the depth of penetration in AJM

- increases ✓
- decreases ✓
- does not change ✓
- initially increases and then remains steady ✓

Material removal takes place in abrasive jet machining due to electrochemical action, mechanical impact, fatigue failure or sparking on impact which one is correct. We all know that abrasive jet machining is a mechanical domain non-traditional machining process. We also know material removal occurs as high energy particles interact with the work piece and in the process the kinetic energy of the particle is converted to the work done in producing a indentation or crater. Thus it is not because of electrochemical action. It is not because of material fatigue neither it is because of thermal action or sparking on impact. So what is the correct answer? It is the mechanical impact that is the major contributor for material removal in abrasive jet machining. The last question.

As the stand off distance increases beyond five millimeter depth of penetration in abrasive jet machining increases, decrease does not change or initially increases and then remains steady. We all know that the jet diameter is typically sub millimetric. It is around 0.5 to 1 millimeter that jet is issued from the nozzle and that jet interacts with the air around us and it flares out. As it flares out, it remains more or less straight over a distance of five to ten d. Beyond that, it does not remain constant that means if you are thinking of a jet diameter of one millimeter it starts to flare out possibly from five to ten millimeter onwards. Thus if you go on increasing the standard of distance at beyond a particular value, there would be reduction in the depth of penetration. So this is my correct answer not the other ones. Now let us go to more complicated problems or solve problems.

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Solved Problem – 1

Estimate the material removal rate in AJM of a brittle material with flow strength of 4 GPa. The abrasive flow rate is 2 gm/min, velocity is 200 m/s and density of the abrasive is 3 gm/cc.

$$MRR_B \approx \frac{m_a v^{3/2}}{\rho_g^{1/4} H^{3/4}} = \frac{2 \times 10^{-3}}{60} \times (200)^{3/2} \frac{1}{(3000)^{1/4} \times (4 \times 10^9)^{3/4}}$$

$$MRR_B = 8 \times 10^{-10} \text{ m}^3/\text{s} = 8 \times 10^{-1} \times 60 \text{ mm}^3/\text{s}$$

$$\approx \underline{48} \text{ mm}^3/\text{min}$$

Here you have to estimate the material removal rate in AJM in an abrasive jet machining process where it is a brittle material with a flow strength of four giga Pascal, abrasive flow rate has been given. Velocity of the abrasive is given and density of the abrasive is also given. Already we have developed a model this is my model. So from this model once I put so two in to ten to the power minus three by sixty that is the mass flow rate of the abrasive, two hundred is the velocity of the abrasive, three thousand is the density and four in to ten to the power minus nine is the flow strength of the abrasive. The second problem:

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Solved Problem – 2

Material removal rate in AJM is 0.5 mm³/s. Calculate material removal per impact if mass-flow rate of abrasive is 3 gm/min, density is 3 gm/cc and grit size is 60 μm as well as indentation radius.

$$\text{Mass of grit} = \frac{\pi}{6} d_g^3 \cdot \rho_g$$

$$\therefore \text{No. of impact / time} = \frac{m_a}{\frac{\pi}{6} d_g^3 \rho_g} = \frac{6 \times \frac{3 \times 10^{-3}}{60}}{\pi \times (50 \times 10^{-6})^3 \times 3000}$$

N = 254648

Material removal rate is given. Calculate material removal per impact. This is another very good indicator. If mass flow rate of the abrasive is given, density is given and the size of the abrasives are given as well as you have to find out the indentation radius. How do I do it? First I will estimate how much is the mass of the grit? I can estimate by this, once I know the mass of the grit the mass flow rate is given, I can find out what is the number of impacts per unit time. This is my mass flow rate this is my mass of a single grit. So these many impacts are occurring per unit time, then I will I will find out how much is the total volume removed in a single impact.

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Solved Problem - 2 (contd)

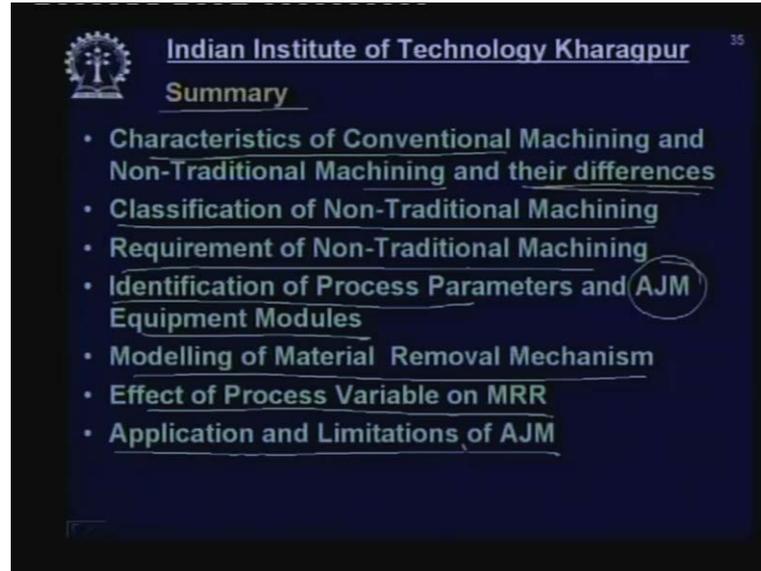
$$V_B = \frac{MRR}{N} = \frac{0.5 \text{ mm}^3 / \text{s}}{2546648 / \text{s}} = 1.96 \times 10^{-6} \text{ mm}^3 = 1960 \mu\text{m}^3$$

$$\text{Indentation volume} = \frac{2}{3} \pi r^3 = 1960 \mu\text{m}^3$$

Indentation radius, $r \approx 9.78 \approx 10 \mu\text{m}$

Because I know material removal rate I know number of impacts. Thus I can find out what is the amount of material removal in a single impact. Once that has been done we have all ready assumed the crater is hemispherical in nature. So I know how much is the volume and i can equate that to this particular volume of 1960 micron cube. So indentation radius we are getting ten micron. So through these two problems, there are two things to learn. We are getting a typical indentation radius which is around ten micron and we also got a typical MRR which is around 48 millimeter cube per minute. So it is in tens of millimeter cube per minute, not in hundreds neither it is 0.1. So these two solved problems not only are giving you expose to this but also giving typical industrial values. Now to conclude, let us come to the summary of today's lecture what we have learnt today.

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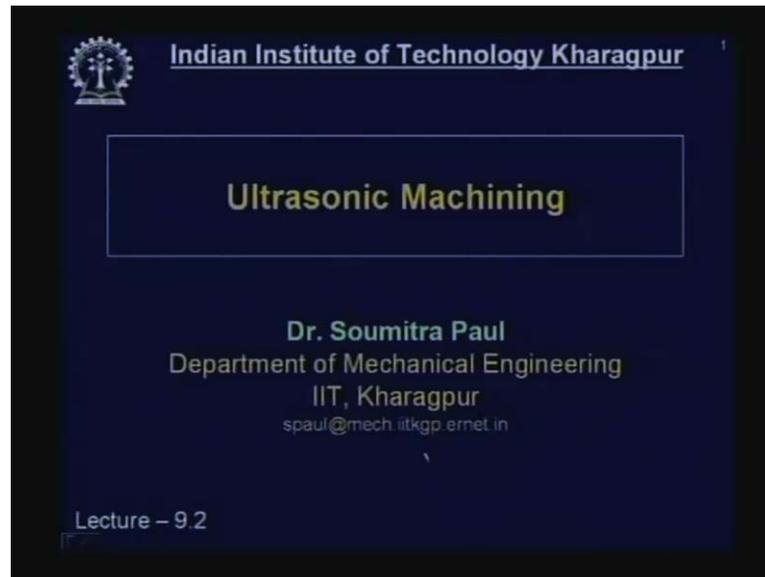
We have learnt about the characteristics of conventional as well as non-traditional machining processes and once we have identified them, we can also differentiate between we can also differentiate between them. Another very important thing we have learnt that is the classification of non-traditional machining process. There are different types of non-traditional machining process. Today we have discussed abrasive jet machining which is a mechanical process, then why there should be non-traditional machining process conventional machining process was doing it fine. So there was some traditional that has also been explained. As far as AJM is concerned, we have identified the process parameter equipment modules. We have also discussed how to model material removal rate. We have studied the effect of process parameters on material removal rate and as well as we have indicated the application areas and limitations of abrasive jet machining. So with that I conclude.

Thank you so much.

Manufacturing Processes II
Prof. S.Paul
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

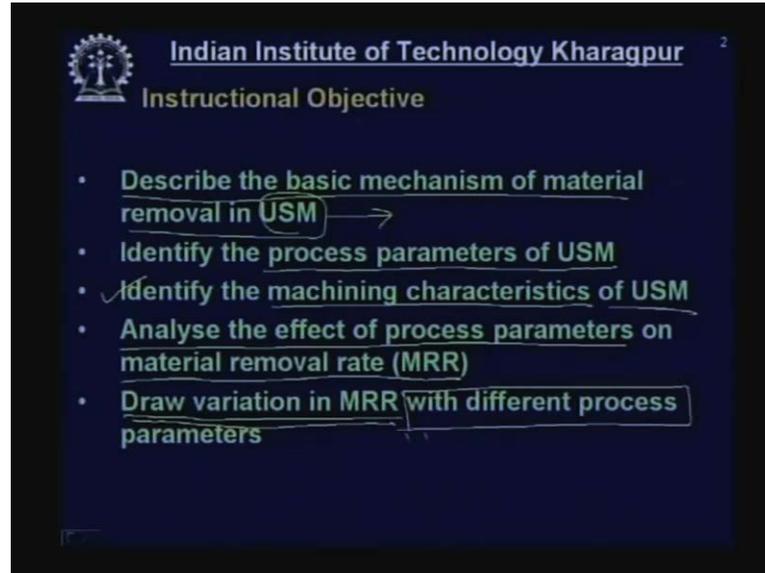
Lecture No. 36
Ultrasonic Machining
Class on NPTEL sponsored Manufacturing Processes – II

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Today we are going to discuss Ultrasonic Machining which belongs to the module number 9 on Non-Traditional Manufacturing. We have started module number 9 with abrasive jet machining. So today is our second class. So lecture today is 9.2. I am Soumitra Paul of department of Mechanical Engineering IIT Kharagpur. Before starting with the lecture, let us go through the instructional objectives.

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The slide is a dark blue presentation slide with white and yellow text. At the top left is the IIT Kharagpur logo. The title 'Indian Institute of Technology Kharagpur' is in white, with a small '2' in the top right corner. Below the title is the subtitle 'Instructional Objective' in yellow. A list of five bullet points follows, each with a yellow checkmark and underlined text. The first bullet point has an arrow pointing to the right. The text in the list is: 'Describe the basic mechanism of material removal in USM', 'Identify the process parameters of USM', 'Identify the machining characteristics of USM', 'Analyse the effect of process parameters on material removal rate (MRR)', and 'Draw variation in MRR with different process parameters'.

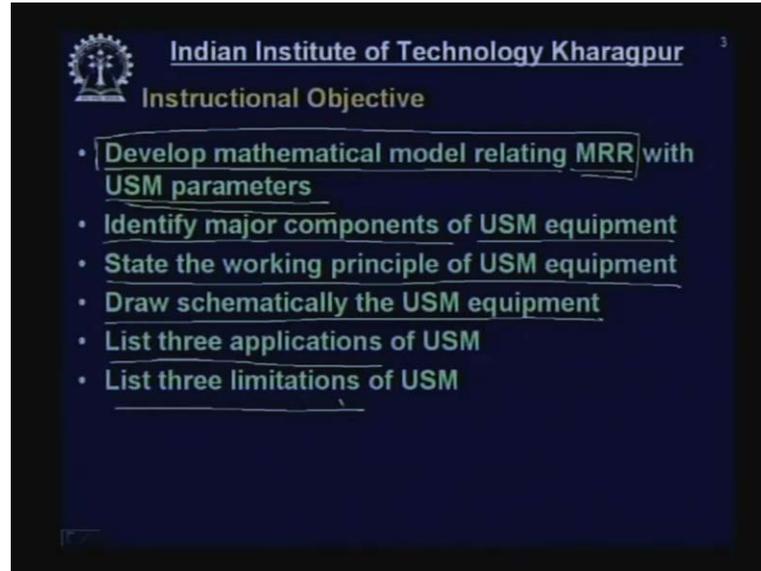
Indian Institute of Technology Kharagpur ²

Instructional Objective

- Describe the basic mechanism of material removal in USM →
- Identify the process parameters of USM
- ✓ Identify the machining characteristics of USM
- Analyze the effect of process parameters on material removal rate (MRR)
- Draw variation in MRR with different process parameters

Once you go through this particular lecture, you would be able to describe the basic mechanism of material removal in USM. What is USM? USM is ultrasonic machining. You would be able to identifying process parameters of ultrasonic machining. In any machining process, machining characteristics is very very important. So once you go through this lecture you would be able to identify the machining characteristics of ultrasonic machining. Describing something or identifying something is good. But you would also be able to analyze the effect of different process parameters on one of the most important machining characteristics which is material removal rate or MRR. Once you have done that, you would be able to draw variation in MRR that is whatever is the variation in material removal rate when some one is changing different process parameters.

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The slide features the IIT Kharagpur logo and name at the top. Below it, the title 'Instructional Objective' is displayed. A list of six objectives follows, each preceded by a bullet point and underlined. The objectives are: 1. Develop mathematical model relating MRR with USM parameters; 2. Identify major components of USM equipment; 3. State the working principle of USM equipment; 4. Draw schematically the USM equipment; 5. List three applications of USM; 6. List three limitations of USM.

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Instructional Objective

- Develop mathematical model relating MRR with USM parameters
- Identify major components of USM equipment
- State the working principle of USM equipment
- Draw schematically the USM equipment
- List three applications of USM
- List three limitations of USM

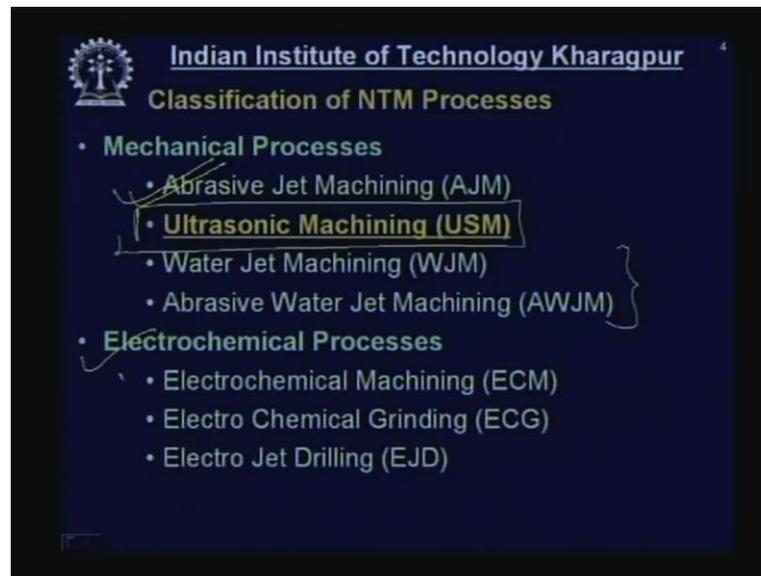
Other than that you would be able to develop mathematical models relating material removal rate with different USM process parameters. Understanding the basic effect of process parameter from experimental data is one thing and developing full mathematical model gives you much more better insight in to the process. Any non-traditional machining process or for that matter conventional machining process requires equipments. So, for ultrasonic machining there is a ultrasonic equipment. So once you go through this lecture, you would be able to identify the major components of ultrasonic machining equipment and state working principle of those modules or sub modules. You would be able schematically draw the ultrasonic equipment and like any other non-traditional process that we are covering in this module you would be able to list at least three application and at least three limitations of USM. Now let us go into the classification of Non-Traditional manufacturing process. Earlier in my first lecture on introduction and abrasive jet machining, we have already gone through the classification. So once again we will briefly touch upon the classification of non-traditional machining processes.

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You have mechanical processes, you have electrochemical processes, you have electro thermal processes and chemical processes. So these are the broad areas. Within mechanical processes, we have already discussed about abrasive jet processes.

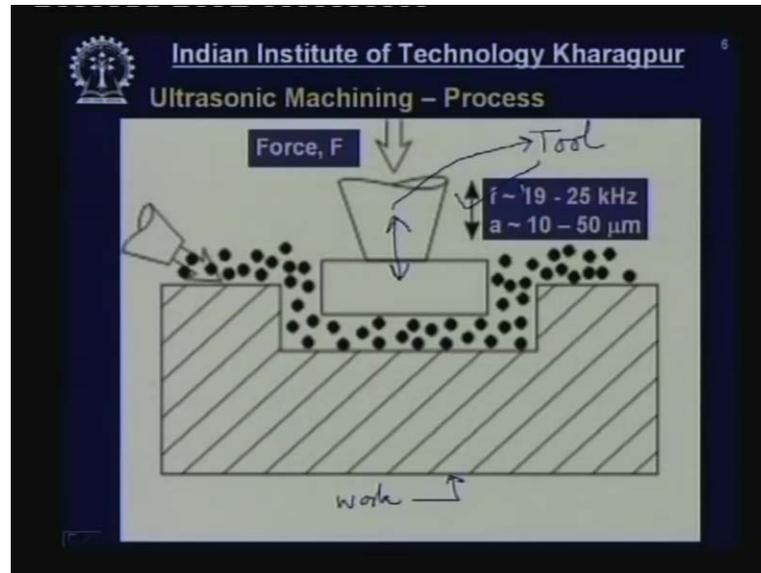
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Today we are going to discuss about ultrasonic machining processes. Later on we will be discussion about water jet and abrasive water jet machining processes. In electrochemical machining, we will be discussing about ECM. In electro thermal processes we will be discussing about electro discharge machining EBM as well as laser machine. But, today we

would be concentrating only on ultrasonic machining processes. So let us come to the process description of ultrasonic machining.

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Like any other machining process any other non-traditional machining process, you are interested in machining a work piece. So this one is my machining, this is my work piece and there has to be a tool with which I am going to machining. This is my tool, this tool vibrates over the work piece. With what kind of vibration that vibration is around 19 to 25 kilo hertz.

Thank you.