Advanced Machining Processes

Prof. Shantanu Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur

Week - 01
Lecture - 01
Introduction: Advanced Machining Processes

Hello and welcome to this advanced machining processes course. I will be an instructor for this course. I am Shantanu Bhattacharya. I work at IIT Kanpur, Department of Mechanical Engineering. In the review, in the introduction session, I had mentioned about the utility of such advanced machining processes in today's world because of the changed requirements of engineering and the demand for performance on creating new materials, new material systems which would be high performing in terms of their engineering applications. It is very important to develop such processes which would allow energy in all different forms to approach material so that there can be material removal possible, there can be different shapes and sizes possible.

And because of that it is important to understand, it is important to also work in a domain which is slightly away from metal-to-metal conventional machining where energy can be brought in either thermally or you know energy can be brought through packets of photons or light, energy could be brought for example, through chemical machining route or electrochemical machining route and still the same activity of material removal be done with all these non-conventional processes. So, I am here to sort of give you a review in this particular course about such processes, the models associated with them, some fundamental concepts associated with these processes, and also perhaps some application-specific you know issues that I will talk about of such processes. These are very very important from a standpoint of modern-day miniaturized manufacturing particularly. When we talk of miniaturized systems which are of scales beyond comparison, I mean you can actually do micro machining, you could do nano machining based on some of these processes.

So, these processes are kind of close by or some of them were really required to make such kind of small minuscule material removal possible within engineering you know materials or engineered materials which are of high utility. So, let us look at this course from a standpoint of the history of what material removal was before, what it was perhaps towards the beginning of you know last century, and then how it evolved into the advanced machining domain in the next few slides. And then probably in this particular lecture, I will also discuss the course content to end this lecture and give you a better idea of what is going to be the expectation on this particular course. So, let us talk of the different processes of manufacturing which are used for making engineering systems. Generally, we classify manufacturing into primary processes and secondary processes.

Primary, of course, is a set or a group of processes which gives the basic shape, the fundamental size of the material. For example, processes like casting or forming, or shaping are generally made because you want to make an overall size or shape to the otherwise available material which is in raw state. And you basically start with something so that it becomes easier to fine-tune that system to any engineering application on basis. So, basically, the need for the secondary processes arrives over the parts which are produced through these primary casting, forming, and shaping processes. Now, secondary processes, of course, involve material removal to some extent even material joining so that when we talk of two parts or more than two parts participating in some kind of a engineering assembly, we need to be careful about the interrelationships between them so that there is energy transfer possible through such mechanisms.

And therefore, the surface integrity, the tolerance, the finish you know related to such interactions between surfaces of different parts come handy for which you need to change the topologies of these surfaces. So, the primarily manufactured processes or primarily manufactured materials are amenable to such changes before they really can participate. They cannot be directly taken into engineering assembly and the purpose of course, of all you know manufacturing today is to make value addition so that there is economic wealth which is generated and that can only be possible if you can develop certain machines out of these manufacturing processes which would result in you know simple energy transfer or even you know motion transfer or something where there is conversion of one state of excitation available into completely different form of excitation which is available. So, therefore, you need machining processes and advanced machining is one domain of such machining processes. Also, you have to understand that as we are talking of value addition and we are talking of large-scale manufacture, there is a requirement of a lot of engineering parts which would come into systems and there can be many types of such engineering parts, and very often because we are making large scale production facilities which are catering to large population as such.

It is about the numbers which is very important. So, you have a large number of units which are being produced in multiple centers of production and therefore, if the parts that were to be designed were interchangeable somehow so that you could have easy fitment of one when the other shots falls short with certain specific tolerances, some dimensional accuracy, some surface finish they become very vital for the functionality of large-scale production as such. So, advanced manufacturing processes are very important for assuring such interchangeability after their primary role of material removal which would be enabling such primarily manufactured parts to go into engineering assembly. So, machining involves in general the removal of some materials from workpiece in order to produce a specific geometry at a definite degree of accuracy and surface quality and of course, conventional or advanced all contribute towards such removal processes in manufacture. When we historically look at this problem of when machining started really, we can date this back to a long time almost the Paleolithic stone tool, Paleolithic age when the very famous the first kind of shaped objects were found in the literature of humankind.

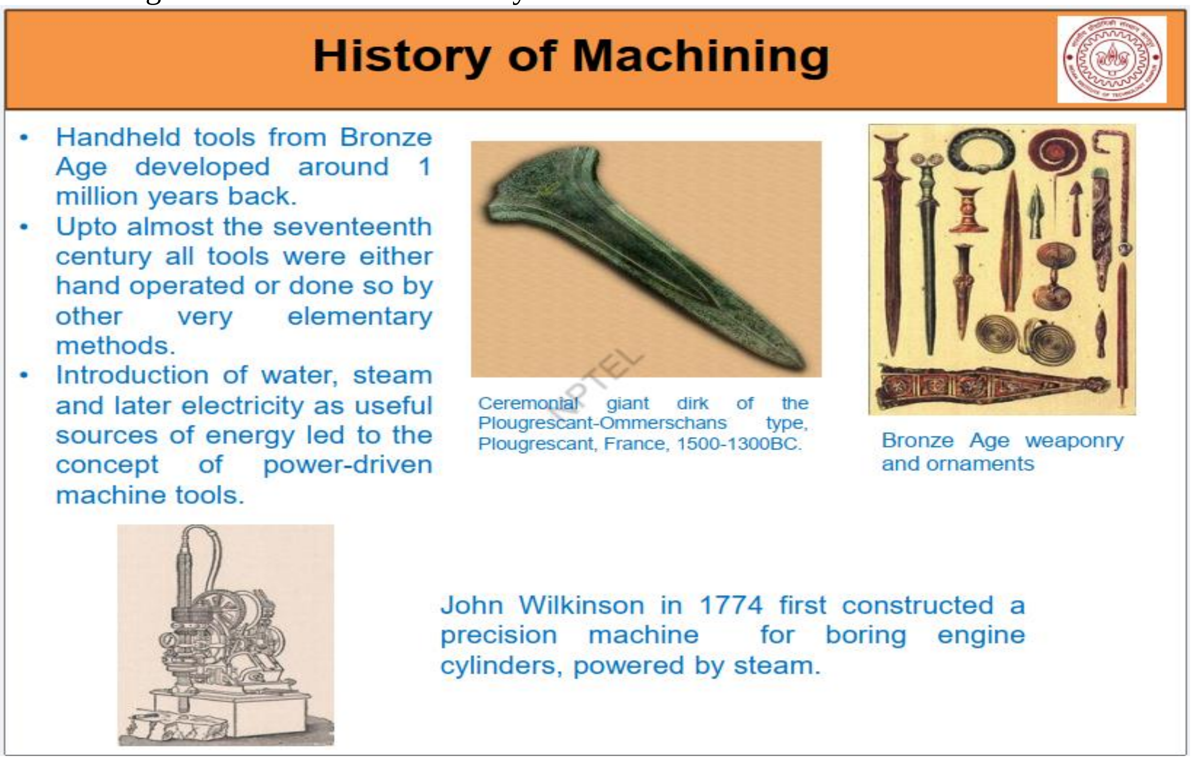
So, one can look at some of these illustrations borrowed from the internet where we are talking of the most ancient Paleolithic stone tool industry the Oldowan which was developed by the earliest members of the genus Homo as such Homo habilis around 2.6 million years ago. You can see some of these you know choppers or burians or alts or you know the spearheads which were made out of simple rock, simple morphological features which are otherwise geomorphological features which are otherwise available, and it was used for a purpose of hitting in order to hunt. In fact, humankind was dependent on food typically by hunting and it was a need based which produced such requirements of making things sharper so that you could throw at a distance, and you know hit something you know a life form so that it could be consumed. That is the history of starting all of this machining processes.

Of course, mankind has used bones, it has been you know using sticks and stones, hand tools since very early on times. A very interesting example I found is that of these nets and bolas which are actually typically hurled around in a rope. So, you have a rope tied along this spherical ball made out of stone and then you can actually use the momentum you know of that particular ball and hurl it in a circle and then throw it so that it can go tangentially from the circular direction into

a certain direction in which the target is where it has to go and hit and create an impact. You can see the nicety or you know you can see the total sort of round shapedness of this particular object and you should appreciate from a fact that there was really no concept of any dedicated organized material removal then and still you could have certain shapes like these produced. So, this is kind of historical mark of where machining really began.

You could find a lot of other examples throughout the internet. For example, the next possible generation of machining happened somewhere around Bronze Age which developed 1 million years back. These are some ceremonials you know darks as well as some Bronze Age weaponry and ornaments which are available throughout the world on excavations, and they are a little better than their older parts you know the older counterparts made of stones or rocks. As such they have a degree of sharpness, some planning, some designing which has gotten involved now as a function of the learning that humankind had from 2.6 million years all the way to about 1 million years back.

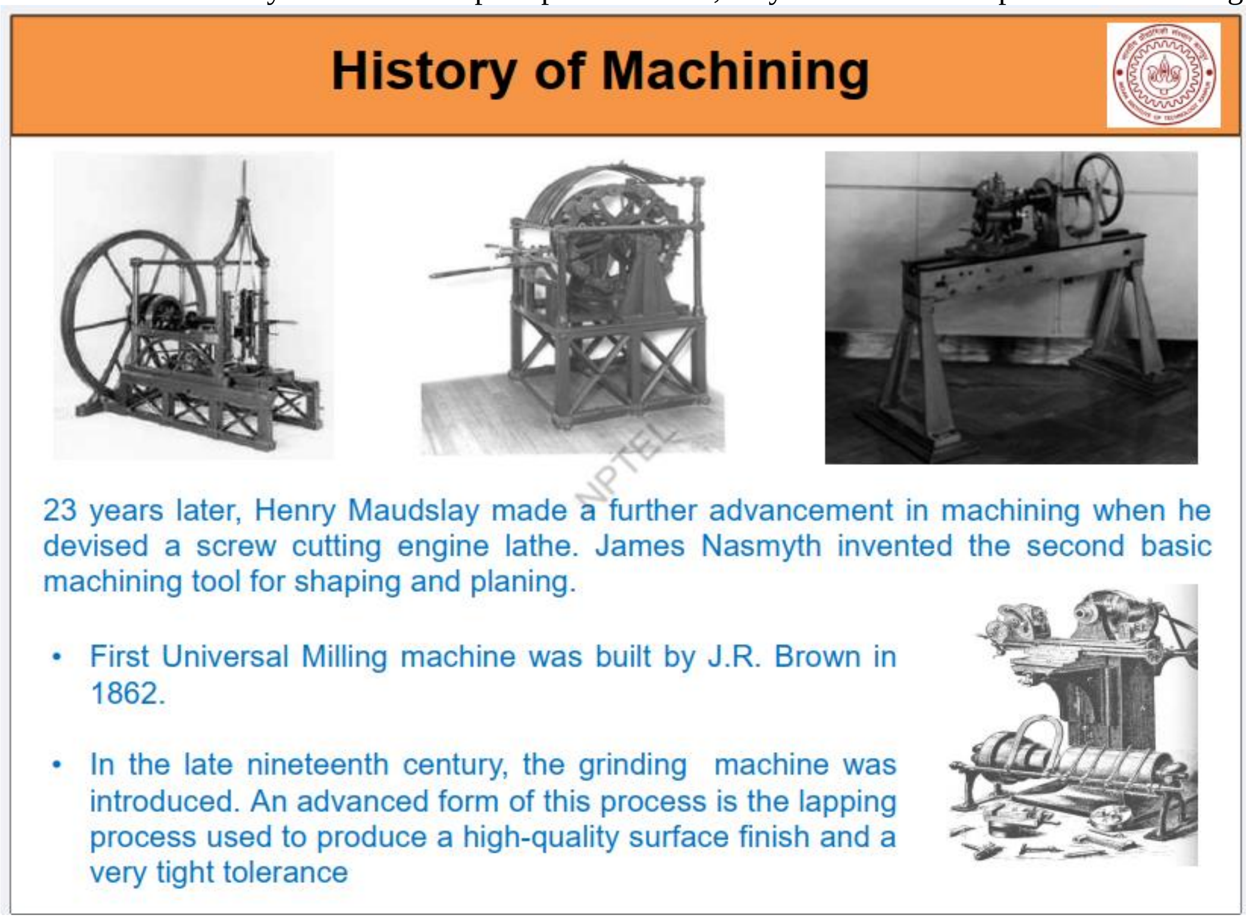
So, that is how the Bronze Age equipment was or weaponry was, or even ornaments were. Now all this continued all the way to almost nearest time frames that we can envision of when there is good documentation etc. available which is the 17th century when there were tools which were there to do such machining jobs, but they were either hand operated or done by other elementary methods. And so, there was an issue of how accurately or precisely they can shape materials, there was an issue of how fast they could produce and therefore people started looking at alternative sources of energy which could do this process of removal by contacting surfaces together in an organized manner. And there was the use of water and steam and later on, electricity as we know off and on for emergence of this concept of so-called power-driven tool which is today available across the length and breadth of our society.



Now there could be various different kinds of machine tools which emerged because of the power made available to them suddenly through steam or water, running water, or for example, electricity, and one can imagine that from the time when people were using either horsepower or you know even just their hands and human effort and muscular effort. It was a big change because people realized that with this power they could work for longer time frames, they could work more precisely by delivering the power in precise packets, etc. so that you could shape better, you could size better some of these equipment's or some of these machine parts which would be developed or manufactured parts which would be developed. So, the first instance that one looks across is this John Wilkinson's precision machining center. This is a boring machine in fact for the engine cylinders.

They needed to be bored and horned because obviously there was piston movement which was there and that should happen in a certain topological integrity. There should be some relationship between the moving piston and the walls of the cylinder across which it would move. And so therefore a rapid and precise technique of giving the fineness of machining in terms of tolerances and finishes on the internal walls was a need. So, this was a steam-powered equipment of course made by John Wilkinson in 1774. The other versions of such equipment which came out later for example this famous screw-cutting engine lathe which was made by Henry Maudsley about 23 years later.

There was this invention made by James Nasmyth who invented the second basic machine tool for shaping and planning. All were powered systems now. So therefore, there was either steam power or electricity power coming in. The first universal milling machine built by J.R. Brown in the year 1862, even today we find J.R. Brown and Company machines very old you know machines in relatively older workshops kept around. So, they were one of the pioneers in making



this milling machine, universal milling machine. And then of course the processes which were adding more finess to the surfaces which were in terms of abrasion or grinding happened towards the beginning of the you know towards the later part of the 19th century.

So, the grinding machine was introduced somewhere around the 1900s. This was an advanced form of machining which enabled the surface to be quite smooth, quite accurate with probably minimum possible roughness. And it was giving its way into a domain where there could be sliding action between machine members because of the lower you know overall surface average roughness etc. which was made on the parts enabled by such processes. Now advanced form of this process is of course lapping which is used to produce really high-quality surface finish and a very tight tolerance.

So the lapping process is different in a way than the grinding because it produces a much more smoother surface. In fact, it is a round plate which works on some fine grains of abrasives and tries to pull out very small micron level you know topology from the, create a micron level topology on the surface. Another thing of course is a wheel which has bonded abrasives. Of course, there are other variants of the lapping process for example polishing with loose abrasives again and again you know polishing pads which are essentially some kind of separate you can say fine paper which contains abrasive grains embedded, etc. So, such variants of grinding along with the grinding introduced a lot of leeway for machinists who could actually produce parts which were quite amenable to sliding, quite amenable to you know less energy loss, lesser amount of joining or you know welding because of relative motion, and it was amenable to building engineering systems in this capacity.

Now when I talk of the historical path of machining of course the later part of 19th and 20th century increasingly had electrically powered tools. The manual effort or even the effort done through hydraulics or for example, steam power reduced substantially and there was an increase in the electrical powering of all the machines. There were lot of further refinements which were made for instance there were multiple point cutters for milling machines which were developed. The whole machining paradigm however was still concerned with somebody who is at sort of adjusting the cutting tool with reference to the surface and some human intervention which created this whole issue of material removal and that created a lack of homogeneity because obviously the accuracy and the repeatability of processes when we talk of large-scale production gets severely affected because of changed human aspects or skills. There may be a very skilled machinist who may be able to produce something which is wonderful and at the same time if you look at the average level of production and the quality in the overall shop floors it may be different because the skills may change from people to people.

So there was a concept around this building at that time particularly because of the requirements imposed by the mobility industry, the aerospace as well as the automotive industry that can we make systems or can we make processes which can address this repeatability issue and the accuracy that comes out of such parts should be highly repeatable between the different systems and this led to of course there were several related developments which happened for example in 1945 the famous controller was developed by G.C. De Waal which was more like a magnetically assisted device when you play something to it, it records and sends you back the signal. So all these developments related to in a related manner in the same time frame led to the concept of what we today call numerical control of machines where this started initiative it started as an initiative in 1953 which led to several different controls for example distributed numerical control, direct numerical control, computer-assisted numerical control and different processes which would allow the operator interface, on one hand, to vanish completely from the machining paradigm, on the other hand, to structure through commands or processes which would give exact you know parity in terms of what they would do as output and therefore there would be a lot of you know parts developed with relatively very high level of repeatability and accuracy using this technology. Now it also became very rapid because numerical control of course could be carried out over more number of hours than any human beings or set of human beings could carry out and so the overall yield of machining, the overall you know aspects related to the accuracy of machining were completely changed because of the advent of the numerical control.

So, the present capabilities with this CNC-NC system has been to the level of a surface integrity of plus-minus 1 microns at a very very high yield. Now there are certain mandates where we also start needing super finishing processes away from the 1 micron plus minus topology where we go into the submicron domain and then still carry out machining and for that, there is a variety of systems or advanced manufacturing processes which have come up in that domain to address the need. For example, I will be teaching something like MRAP, which is called magnetically assisted rheological flow finishing system, and there rheological fluid assisted flow finishing system where we are talking of even something with an integrity of plus-minus 100 nanometers or 200 nanometers. So, the whole essence of the developmental process of the technology is about how accurately you could manufacture the surfaces so that they could interact in a more favorable manner and a more you know energy-saving manner and produce some value addition or economic wealth to the society. So, this is in a way a sort of a introduction of this history and I need you all your you know young and budding students who are working in this area more at a postgraduate level, or even some of you are finally undergraduates.

So, you should understand and appreciate what was the foundation on which machining started and where we are today, and where what we are addressing today in our technology. So, in modern machining practices as I told you the first development which has happened is the ability to scan across a landscape of hardness you can go to harder, stronger, tougher materials. Materials which are engineered today you know from a standpoint of strength requirements imposed by various engineering systems. Materials which are developed through processes of alloying or even you know compaction or even composites which are specific to a certain job. So, the process that you develop in machining in the modern era today should be independent of what is these material properties.

You should be able to cut, or you should be able to remove material amicably respective of how tough, how strong, how hard a material is. And of course, the other challenge which is there is from shape complexity because earlier when the whole conventional domain was envisioned, and we started building up systems with the kinematics between the tool and the workpiece and the relative orientations of the tool with respect to the workpiece. Nobody thought of how you would produce anything away from symmetrical parts because we would generally look at rolling, we could generally look at you know circular motion, we would look at linear motion, we would look at some motion you know controlled in a guided manner. And it would not result in a very complex topology which is the requirement of a lot of systems today. For example, look at the aerofoil shape, it itself is a very complex topology.

And what is there in the machining domain that could address that job was also is also a fundamental aspect behind advanced or so-called non-conventional machining that should be looked at. So, ability to have more and more you known amenable material properties from engineering standpoint, the ability to be able to define shapes and sizes according to the highest level of complexity. And also, the ability of combining two or more different processes which we also call hybrid machining which leads to the primary material removal at a much higher rate and a secondary stage material removal at a slightly lower and more fine-tuned rate producing the required integrity. All these concepts have to be integrated when we start thinking of advanced manufacturing processes. On to the top of all this, there is a complexity introduced by miniaturization in various engineering systems as is applicable today.

There has been miniaturization in electronics, miniaturization in mechanical systems, miniaturization in you know a sort of hybrid system which we also call as microelectromechanical systems where you have the ability to go small scale to the level of almost atomic precision or atomic resolution with the systems and processes that are available today where you know you can do very useful scaled down you know behavior which is of importance to the society. So, in that mandate, I would say that the advanced machining techniques fit quite a bit, they have a lot of overlap, and they have the processing capability of going almost to atomic resolution or precision. And that is where the modern machining paradigm kind of evolves because of all these needs which are there in the industry. Now, there are machines like precision kinders today which are capable of producing an accuracy level of plus-minus 1 microns. You can measure that with light energy, electromagnetic radiation with lasers you know instruments which have optical fibers.

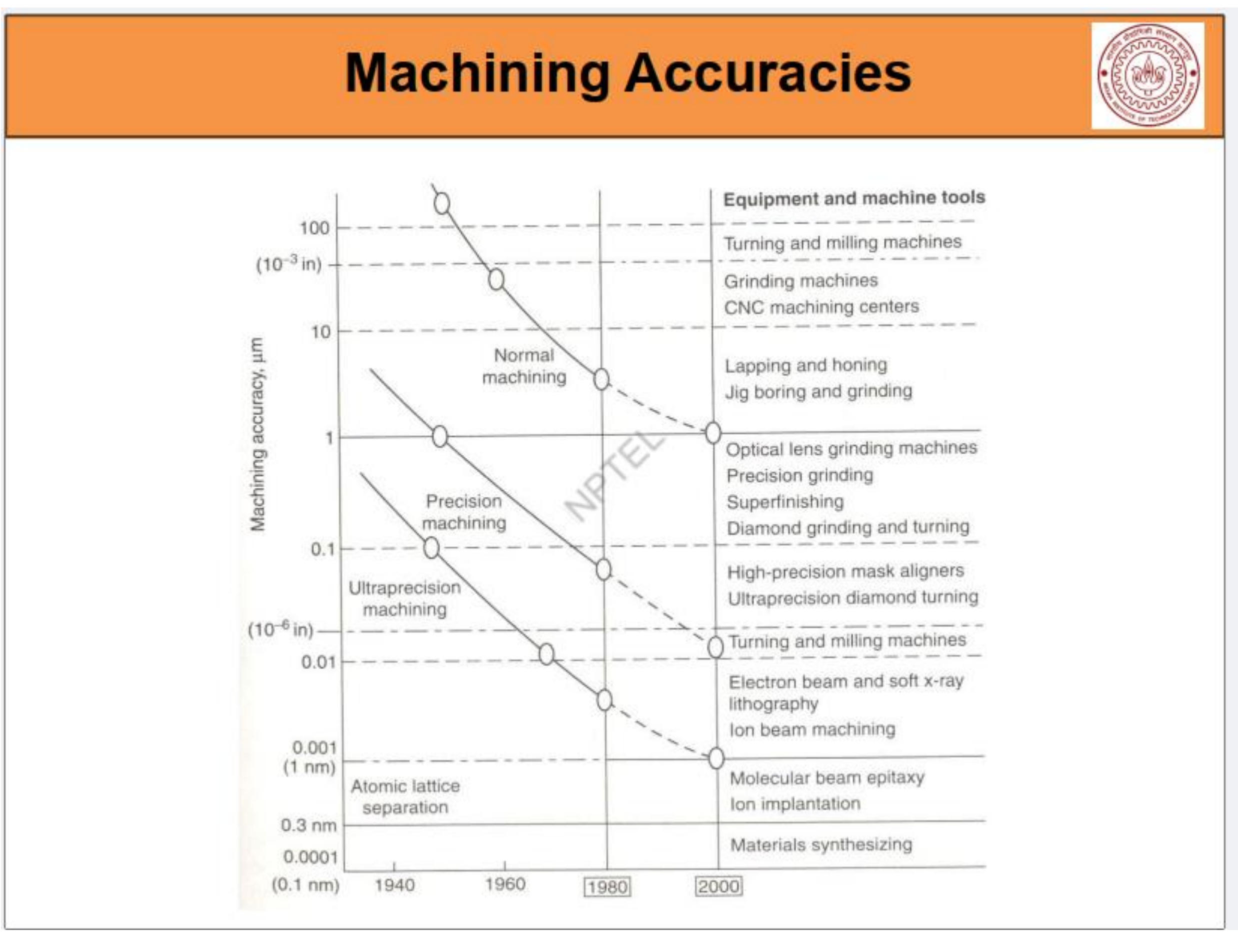
Of course, the other biggest issue that I would like to talk here is that not only is the ability to process to a certain level important, but also the ability to be able to see whether the process has taken its necessary consequence, whether it has gone to that level of integrity that is also very very important. So, it is not only the ability to create but the ability to decipher whether something has been created which has to also be parallely developed. So, therefore, instrumentation is available you know which can go up to microns, submicrons, nano even like atomistic precision, and be able to characterize what is happening at that level when you are trying to add remove materials. Also, when you are talking of small material removal a very important issue is small material addition because obviously, you are wanting to build up surfaces with not only removal but a combination of removal and addition. You have almost all of you are familiar with the term additive manufacturing.

There is a need increasing need that how you can be sustainable in terms of your processes, how you can be able to remove you know minimum possible or waste minimum possible material to be able to generate something which is useful. And for that, it is perhaps not a one-path strategy of only removal, but also the coupling of the term addition to the removal which becomes very very important. And therefore, in the recent trends of micromachining or nanomachining, you have an additional way of how do you shape existing materials, how do you remove existing materials and how do you add existing materials to create the flexibility of shapes and sizes which would do its job of some important contribution, some important effect you know to the area of science and technology. So, there are future trends which you know uses for this purpose variety of electromagnetic radiations starting from visible radiation to ultraviolet to almost going up to x-ray or even high gamma rays you know radiations which create enough precision in terms of their resolution to be able to read number 1, number 2 and find out or characterize and also in terms of what they built on polymeric films or on you know surfaces which are perhaps non-conventional and can go to very very high level of accuracy for defining the features at smaller scale. I would like to illustrate the LIGA process, which is lithography of Fermung, Galmana-Fermung which is actually a process where you are having deep lithography done through x-rays where you have high impact, high aspect ratios of structures produced at the level which is perhaps submicron even all the way to a few 100 nanometers.

And then you can actually have coating you know electro-coating on the surfaces to make parts which are sort of mimicking what metallic parts could otherwise do, but at a scale which is not realizable by direct materials or metals. So, such processes do exist quite a bit in the modern paradigm of machining you have nano machining. It is a very recent trend in these processes where atoms and molecules are removed. I think I have talked about, described about this process you have something called a molecular beam epitaxy where you could actually generate layers of different materials. For example, if you look at 3-5 materials you know where we create some kind of a photodetector or some kind of a you know photodiode effect.

You have the need of going very small, very precise, and be able to create such devices, today available within a few you know tens of nanometers range. It is not possible without some of these non-conventional or advanced machining techniques. Of course, the concept of nano machining was introduced by Taniguchi to cover the miniaturization of components and tolerances in the range from submicron all the way to individual molecules, all the way to 0.1 nanometer which is an Armstrong precision, atomic precision. And for that you know I would like to share how precision has taken shape across the years.

Of course, the data available here is up till 2000, there has been a lot more in the trend proceeding the 2000 which perhaps I will share at some later on point along this course. But as you can look at on the y-axis here in this particular curve, we are talking of machining accuracy you know all the way to 0.1 nanometers from somewhere around sort of 100 microns. And on the other hand, you have on the right-side different equipment and machine tools which are being illustrated. And one can see how the machining accuracy has changed as a function of time.



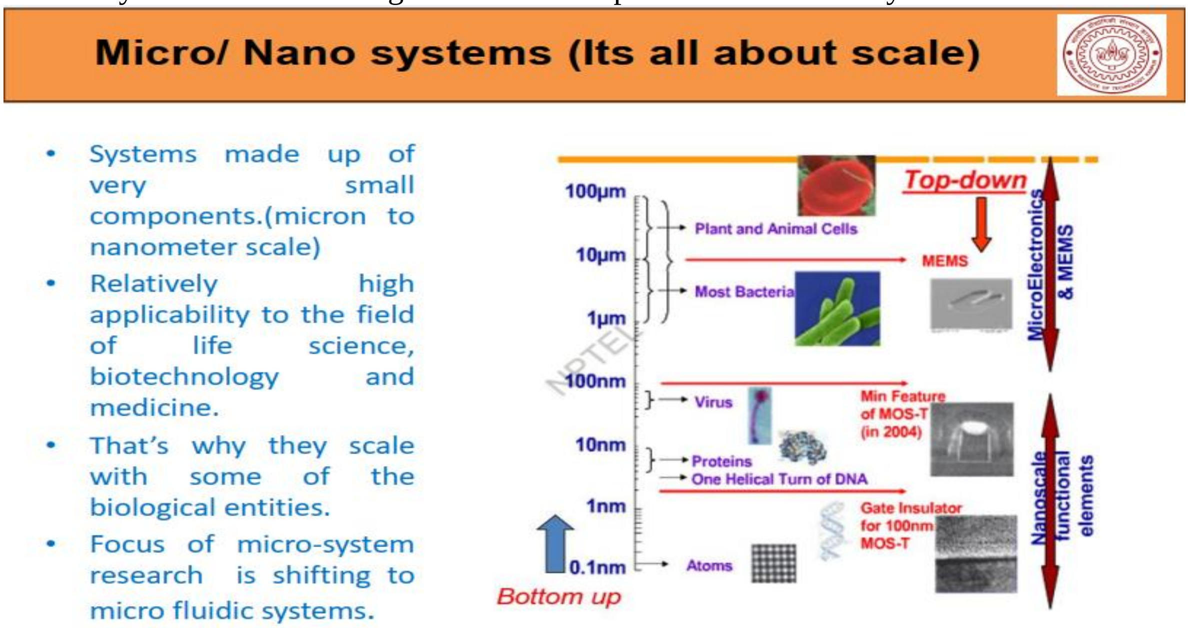
Of course, the x scale is the years, there is a difference of about 20 years which is packaged into all these different you know time scales. And one can see today that the precision available is almost you know even one atomic layer thick material which can be done through ion implantation, molecular beam epitaxy, even self-assembly and material synthesis some of these processes. So, I am going to scan over all this domain, and I am going to give you some illustrations on the various processes which are available for obtaining the different levels of accuracy, different levels of dimensioning, different levels of scaling of materials which we talk about across this course. This slide I generally illustrate in all my lectures because I want to sort of give a perspective of how important it is and where is the society, one of the finest sort of you know angles from the society or the requirements of the society are coming for going small and that is the area of detection of biological species. Now in clinical diagnostics or for example, in you know domains related to medical diagnostics it is very important, it is very needed to determine the least you know concentration of any sort of pathogen or biological agent which may create mass destruction.

We are all witnesses to the COVID pandemic which happened a few years back unfortunately and we know how important it is to detect early on. We also know how important it is to you know be able to provide therapy at the right stage so that the criticality or the loss of lives are emanated, and the society greatly is influenced when we talk of such minuscule detection. Detection can otherwise happen of biological agents through macroscopic means on an average basis because you are looking at a lot of species which are creating some effect. But that is sort of high utility because you need to detect them early on or you need to detect them when it is at its young stage, and they have still not been able to interfere sufficiently with the human system to start controlling the human system. And for that, it is important that very precise small amounts of contaminants or you know the biological species which are deleterious to the human health be detected.

So, for that perspective, if I looked at what micromachining has as an option you could have all different sizes and scales which can rhyme very well with some species. I have given some illustrations here. This is what you know there are two aspects of it. One is of course you learn how mother nature is using these molecules and building up higher forms and try to develop based on it through your addition of material concepts. So, you could produce in the same bio-inspired route something which is related to mother nature.

On the other hand, we look at it from a standpoint of if there are these small elements what is available in the domain of machining which can carry out similar sizes or similar shapes so that there is good interaction between the two. So let us say we talk of these atoms you know which are assembled together. The finest form of such an assembly is the DNA which has one helical turn which is close to about 4 to 5 nanometers 40, 50 Angstrom. And you know we are talking of detecting such DNA. So of course, on the other side if I looked at what is available in the scope of machining these transistors which are there, and we call it ISFETs you know ion sensitive or ion selective transistors or even ChemFETs we call it chemical field effective transistors.

They are of almost a 100 nanometers size. This is gone down much more now perhaps 50 nanometers or even lesser. The gate insulator region for such a transistor is about close to 1 nanometer just a few atomic layers. And you can think of that when we are talking of a biological agent, or a biological species immobilized on the top of such a dielectric you know gate dielectric it will influence through its field through its depth of field the you know the drain-source current which is there in the device and that could give you some aspect of sensing an object as small as the DNA or as a protein. Similarly, we talk of viruses, we talk of you know proteins this particularly you know is a virus which is only a few 100 nanometers in diameter you know there were 200-300 nanometers, and they can be even less than 100 nanometers. In fact, the Covid virus is and then that created an issue because sometimes the recognition of cells becomes jeopardized because they are not able to recognize so small a species within the body.

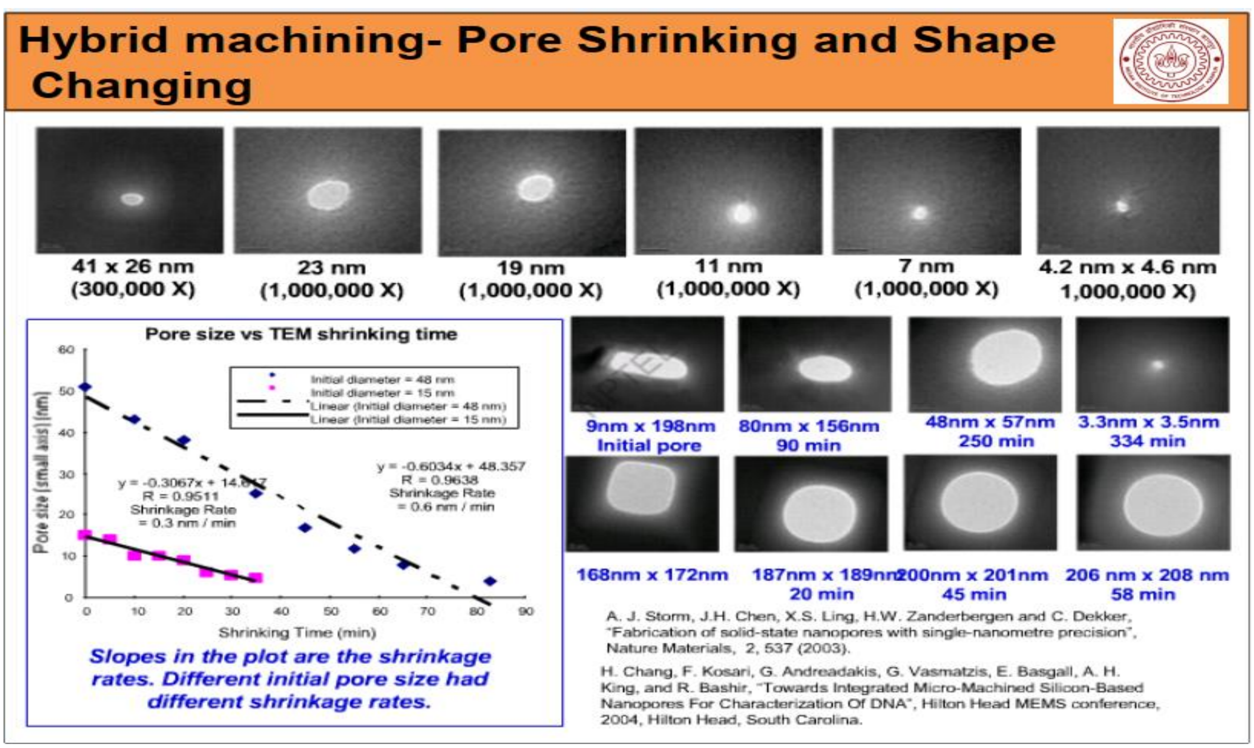


So, proteins again you know which are making these viruses they are typically capsids around the viruses. So, all the genetic material is inside those proteins you have genetic material inside and a capsid outside, and can I detect such a species. And so, there are these again you know immobilization techniques available on surfaces through which very small films which would be field transparent to the immobilization of such species which has proteins which has certain charge on the surface affects the device performance. So how can you realize such levels or accuracies of detection unless you go that small and are able to create that small feature.

You can talk of MEMS devices microelectromechanical systems. Here you know I call it a diving board in a swimming pool kind of structure you have a small you know crater which is there and there is a small lip which is you know coming out as a diving board and this lip is amenable to motion. Of course, there is clearance below it so that you can move it, bend it, or deflect it and so there is the surface immobilization of this lip to several biological agents like bacteria. Most bacteria are about 1 to 10 microns range and some of it sitting on the top of this lip will make the lip to bend or move because of change of surface energy due to the Stoney's principle. And therefore, such changes in surface energy can be easily detected through amenable detection systems in terms of a change in the reflected spot coming across. You could think of a laser beam which hits on the surface and as the material deflects the laser beam kind of you know changes the incident angle or the reflected angle changes and based on it you could calculate what is the degree of deflection which is there.

And so, if there were some species interacting to do that small deflection based on a few of those species that is what we are trying to do because we are wanting to capture them early on. We are capturing things which are not growing any further they have just started the growth process and that happens only because again you have those techniques today in the market which is able to realize these features or these shapes. I think I am able to create some motivation among you as to why or how just this one field of clinical diagnostics or detection becomes so critical for the society yet may be achieved by something like advanced machining processes. Removing of plant and animal cells this is a red blood cell which is again a few tens of microns, and you can make something which is of that size. So, the whole idea is that if I had the power of making things which are small or smaller than the biological species of course we have the flexibility and amenability to detect them very early, very small concentrations and that gives you a lot of advantage in terms of how you treat therapeutically the people.

And so, it is important to relish, to cherish the fact that this whole micro nanotechnology which has come up and lot of footprint of advanced machining which has come up is gearing to some of this very critical domain for the human society. Now when we talk of such an illustration this is a small example of what is removal and how it can help the detection or early detection of something like a DNA molecule. So, you know what this particular schematic or this particular slide shows is something which we otherwise call a nanopore. You know you can look at this particular pore here under a transmission electron microscope and I can find out how the pore size is varying as a function of time. In fact, if I looked at this particular schematic, the first schematic it is at a different scale it is about 300,000 magnification, and later on whatever schematics we are looking at is around almost 10 to the power 6 magnification.



And what we can see interestingly is that there is a small feature here in a TEM or in a transmission electron microscope. If there is a section of a particular surface which is open it comes as a, it is a shadow that we are seeing and this is where the beam is escaping. So, you can see the scintillation you know as if the electron beam has escaped from this process. So typically, a TEM images things in a manner so that a hole is represented through a electron spot which is there and with enough scintillation on the screen where the electrons are falling. Now when I look at this whole pore you know this is of course made in a silicon on insulator.

I am going to talk about this a lot more later on. But you can think of it as silicon and silicon oxide where we are heating the silicon oxide, and the silicon oxide is reflowing. So, you have a layer of silicon oxide over silicon, and you have created a hole somehow and then you are heating it with the beam. So, the electron beam of course is a lot of energy you are delivering that energy, and it is creating some kind of a melt and reflow concept in that particular space. So that the oxide which is around is kind of trying to melt and trying to reflow and of course, there is a surface energy which is there between the gap and the surface and because of which there is a self-closure of the hole which you can see happening here. So, for example you have a 23-nanometer hole time period T1 it goes to about 19 nanometers and it all the way goes to almost about 4 to 5 nanometers.

Now this is what the size of a helical turn of a DNA is. So, if I were to use this pore to translate DNA molecules across. For example, you create a electrolytic flow cell you create this particular you know wafer with this hole orientation in the center of that particular electrolytic flow cell and enrich the DNA solution on one side and let it flow to the other side. So of course, the DNA passes through lot of these small holes and there is interaction between the surface of the hole and the DNA and then you know one can look at the length aspects or size aspects of the DNA and try to understand more about the DNA. Even sequencing can be done through this we call it a nanopore based sequencing there is a technology like this which is available today in the market where with a small nanopore on a polymeric substrate or a silicon you know substrate you can see what is the sequence of molecules on a DNA which actually is very important evidence of what it is representing what it is characterizing.

Now again possible through advanced machining processes. So, if I looked at the traditional side and then the non-traditional side and look at what is the difference really between these sides. Traditional removal processes are based on either normal cutting processes in the traditional sense where there is metal-to-metal machining you can create a lot of these circular shapes or other shapes based on how the process is planned. All of us have looked at turning, boring, drilling, milling, planning, shaping, broaching these are all different variants gear forming, gear generating which come out of the conventional domain. I am assuming that a lot of you who are participating in this advanced manufacturing course have already been witness to some of these processes are back in your workshops or also studied something related to the models of these various processes. And on the other hand, the mechanical abrasion mechanisms are also part of traditional machining.

Again, I think I made a lot of remarks towards the beginning about you know the middle of the 19th century developing some of these abrasion processes. You have bonded abrasives where you could have grinding, honing, and coated abrasives and then of course, you have loose abrasives through which you can carry out polishing and buffing on the surface. The non-traditional on the other hand are not really bringing in a lot of metal-to-metal contact machining but are in a way bringing or approaching energy to the surfaces in other forms. For example, CHM stands for chemical machining. So here you are carrying out machining through a suitably designed solvent which otherwise has etching action or engraving action on the top of a surface.

So, it reacts in a way with the material of the surface and carries out some material. So that wherever the reaction is happening you have an engraved you know region and you can call it a machined region in this manner and you can have removal rate on this manner. You have electrochemical machining where you are talking of Faraday's principles where you have a electrolyte and you have you know you have given some voltages and through voltages you are carrying ion transport or making ion transport happen so that you have electrochemical machining. You could have electrochemical grinding; you could have electron discharge machining this is the way you are bringing thermal energy. So, you create a small discharge which is a momentary plasma which is created in otherwise highly insulating dielectric layer and that brings close an energy packet which creates melting, and you know diffusion of the melt into the suitable fluid which is facing the dielectric fluid which is facing the surface.

So that is called electro-discharge machining. You can bring a packet of photons very close to a surface, making photon-to-phonon interaction possible on the material where photons are converted in terms of bond vibrations. There is a liberation and lot of thermal energy in this way and then there is vaporization of the material which happens or sometimes there is a recrystallization from whatever melting is generated across the vapor point which happens. Of course, in lasers, there would be more of vaporization because the energy density is very high. You have abrasive jet machining where you are carrying out mechanical energy not in the sense of a direct contact of a point over a longer period of time, but in sense of creating packets of mechanical energy delivered onto the surface through something called a moving abrasive. So, you have a high-velocity abrasive grain which is coming to a surface and being pinching in a way and then creating brittle fracture and so that creates material removal or that facilitates the material removal process.

You have water jet machining, the same thing as an abrasive was doing in air could have been done through a water stream where you are bringing in abrasives through a water stream close to the surface or even just water stream directly hitting on the surface also creates pressure area product that is forced on the surface which leads to removal of materials. You can have plasma beam machining or ultrasonic machining based on again you know applying heat energy in one sense and applying mechanical energy in packets in another sense. I am going to look at all these non-traditional machining along with certain other advancements which are there in this area to cater to the micro nano domain as a principle interest of you know area of interest when we talk of non-traditional machine. Now let us look a little bit into the machining by cutting because that is probably the only portion where I am going to have some introductory thoughts for those of you perhaps just begin to get influenced or you know exposed to this process. So, as we all are aware in the conventional processes the tool is penetrated into the work material.

There is a point on the tool which is relatively harder than the hardness of the surface and we are trying to scratch the surface and we are trying to create an impression on the surface through this hard tool penetrating on the surface and creating material removal to happen. So, what is removal really? In this case, you are going to create a force per unit area or a stress which is somewhat similar to the ultimate yield strength of the material so that there is failure which is possible on the material and there is a stripping action which is happening of the material because of such failure. So, obviously, the way that this tool penetration happens is a function of how the path of the tool is on the surface, what path takes also defines what is the geometry of what it is going to produce and the relative motion of the workpiece with respect to the tool in a way determines that what is the final form of the geometry that you are able to get. So, for example, you know if you look at turning processes it produces like cylindrical surfaces or if you look at shaping or planing it generates flat surfaces. You could look at drilling which produces again holes of different diameters and so on so forth.

Now, there are various aspects when we talk of certain material removals one is that there is high temperature created in particularly the zone which is penetrating which is creating a lot of you know mechanical stress. And obviously one of the reasons for the high temperature is that on one hand material is getting cut off. So, there is shear which is happening continuously, the atoms are being pulled out and there is going to be some you know sort of effect to that sense that bonds are breaking and reformulating which will create some temperature rise. Of course, there is another aspect that whatever is coming out is running past the material of the tool which is penetrating and there is a lot of frictional aspect which is there which again creates temperature. So, that is why on the principle shear plane there is a lot of temperature generation also on the rake surface where the chip flows there is a lot of temperature.

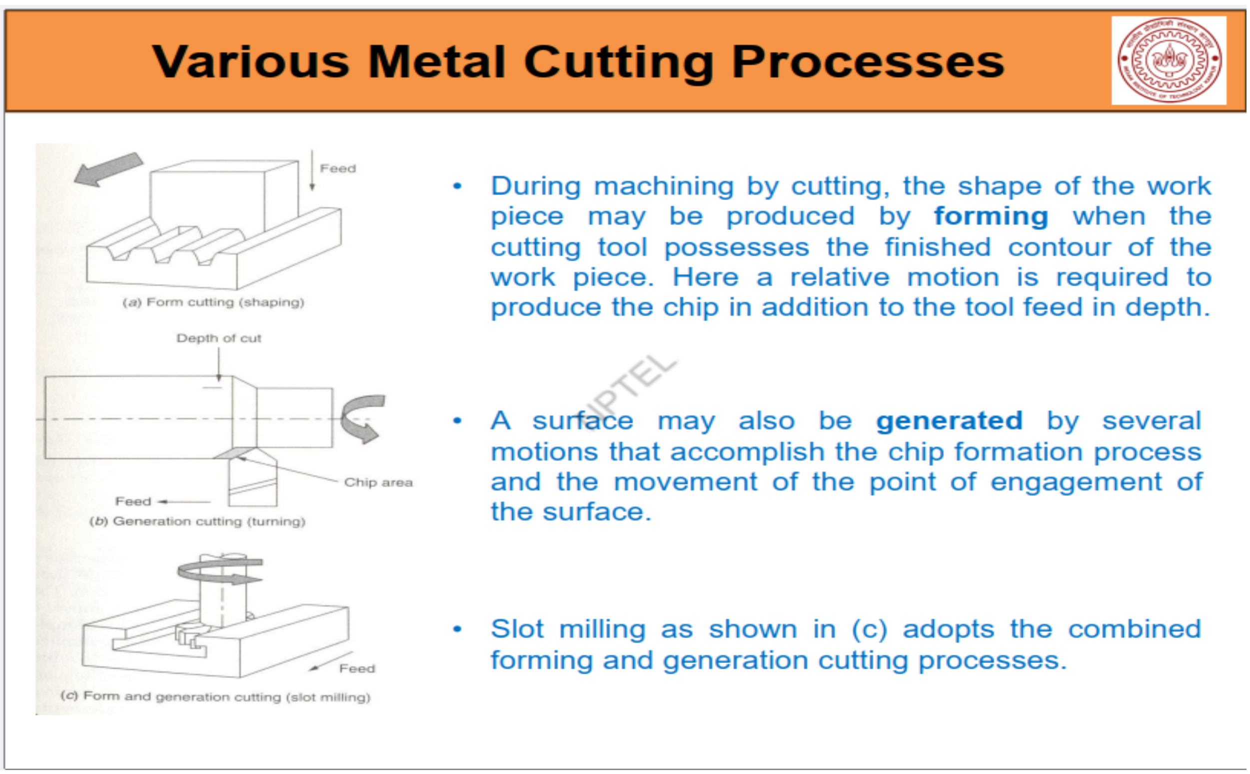
So, there are various reasons for why temperatures should be generated on such kind of metal-to-metal machining. Now, temperature generated in a way is kind of advantageous for the process itself because it starts to get the more process back into flow. There is going to be some thermal softening of the material because of the extremely high temperatures which it results from and that results in better finish perhaps. There may be a reduction in the strength and ductility because of such thermal softening behaviors. So, several people including, for example, El Caddy 1998 they have claimed the formation of continuous chips for example, from discontinuous ones due to workpiece primary heating because of such material you know removal action.

Tor and Coppola they built a laser-assisted system in fact, a prototype which would be preheating the workpiece. So, that there could be thermal softening and there could be a better amount of material removal possible because of such thermal softening with high surface finish. It could also help in reducing cutting forces, it could generate a lot of improved tool performance. One has to remember that there is frequent tool breakage because of the quantum of a thrust cutting thrust that it faces while it digs against you know uncut material. And so therefore, obviously thermal softening helps the behavior of their breakage and the frequency of their breakage, etc.

So, obviously, we can make different illustrations happen when we are talking of the metal cutting process, metal to metal cutting process. One of the illustrations is what we call forming which is basically the impregnation of the tool shape or the negative of the tool shape onto the workpiece. You can see the tool geometry here and can analyze that why this these slots have come because of the negative tool geometry scraping across the workpiece trying to take off material due to a relative motion. This is called formability of the surface.

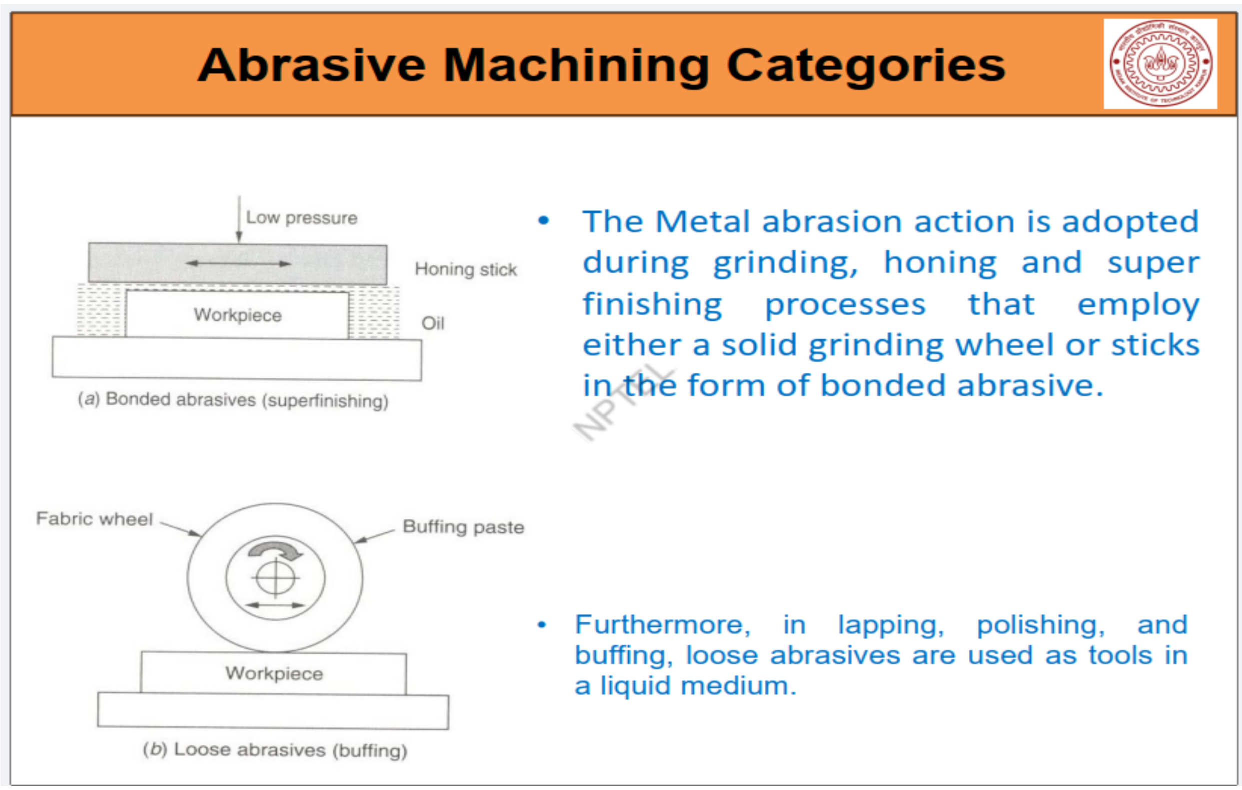
So, you are forming based on the tool's overall shape. You could have a generative approach in carrying out, for example, a simple lathe, a turning center you essentially moving the tool in a axial manner while rotating the workpiece. So, you are creating a geometry which is more like generating the surface. So, we call this generative form of machining, planned motion so that a certain shape gets generated. This is not as good as forming because forming, of course, is based on a prefabricated shape on the tool surface which you wanting to impregnate and create a negative. In this case, it is like just generating a new shape altogether by just motion control without designing any tool surface specifically to that.

You could have again a combination of generation and forming for example, this slot milling operation you know it is kind of indicating a combination of a forming process done through the edges of these cutters as well as a generation process which is about again you know the circular motion of the particular tool which is acting together to do cutting action. And in this way, you can clearly understand how metal-to-metal cutting kind of functions to generate shapes and sizes. Now you could do the same by abrasion. There are the abrasion machining processes where you have machining allowance by removal of multitude of hard grains, hard angular abrasive particles or grains also called grids.



This may or may not be bonded to the form of a tool of a definite geometry. In case it is not bonded you have processes like lapping and polishing where there is free abrasives going around the cutter and the surface. In case there is bonding you can have honing, or you know grinding or some other variants of the same process. Now, in contrast to metal cutting processes of course, during the abrasive machining action, the individual cutting edges are randomly oriented. Cost of engagement is also sort of not so big as the machining and you know you have unequal abrasive grains acting on unequal portions you know or acting to create unequal portions on the surface through brittle fraction process while doing machining. So, material, of course, is removed in form of minute chips which are invisible for most of the time.

And of course, you know one can have other forms like I already talked of this metal abrasion action adopted during grinding, honing, and super finishing processes that employ either a solid grinding wheel or a stick. This, for example, is a honing stick which is doing the same job of course, as a grinding wheel. A grinding wheel is circular in nature, but this is more like a you know shaped like a stick which is going against let us say the walls of a cylinder or something which is creating that abrasion effect. You can have circular processes where through applying of a buffing paste to a buffing wheel or a polishing wheel you know you could create or even lapping process where abrasive is held between a circular plate and the surface you could create again metal abrasion action. So, whatever you have primarily produced in step 1 through the generative forming processes, formative processes you are trying to finish using step 2 of the abrasive processes.



In a way, this is what the I would say the you know conventional technology of machining kind of assimilates. Beyond this whatever is you know in terms of new materials, new processes, complex shapes, and all the impositions that I told about is all advanced manufacturing. So, in a quick manner, I would like to go across you know the various classifications of the advanced machining that are possible. The energy is brought in as I told you are discrete, they are brought from a perspective of either mechanical action or thermal action, or chemical electrochemical action, and on that basis, we are classifying the different processes. Of course, all these processes we will talk in great details, and lot of models associated with these processes we will do along the course.

Now having said that I am quickly going to because also kind of end of this lecture I am going to quickly look across a few slides towards the last which talks of the content of this course. Of course, this has been earlier shared with you, but I am going to sort of start off with week 1 where we talk of some overview-related material on microfabrication using silicon glass processes, an overview of soft lithography, polymer microfabrication, introduction of the use of non-conventional process for micromachining etc. Of course, the introduction I have made today is more on the historical side and that forms the opening remarks of this particular course. We are going to have mechanical material removal processes in great depth in week 2 where we talk of AJM processes, or you know USM processes. We do some first principle modeling based on Shaw's theory where we discuss about how the MRR can be calculated and then try to regress some of the actual MRRs to it to find out what are the relevant coefficients between the basic model and the actual you know the real world.

We will continue this into week 3 as far as possible depending on the time which is available. Then we will talk of you know week 4 which is again on the abrasive water jet side where we are describing the process where there is an abrasive brought in close to the surface through a stream of water. We would look at different finishing processes here in this particular week we talk of abrasive flow finishing, magnetorheological abrasive flow finishing, physics of MRAF you know we do some detailed models related to the MRAF and try to understand and finish everything related to mechanical abrasion of abrasives or mechanical abrasion given through abrasive particles on surfaces. Week 5 we will try to delve into how material is removed electrochemically. So, we will look into some of the basics of electrochemistry.

We will look into how iron is transported as such within materials or within electrolytes. We will look at how to estimate the material removal rates and the parametric optimization of some of the key parameters for carrying out such a dissolution electrochemical dissolution. And then we can also look into multiphase alloys we will try to in week 6 try to do some modeling kinematics, modeling of kinematics, and dynamics associated with the ECM process. We will also have a numerical approach to the whole ECM trying to do shape determination in of the electrode given a certain required shape that has to be embedded. We will also design the electrolyte flow considerations; we will also do electrolytic flow dynamics and design of electrodes as such for proper coverage mechanical coverage of the area.

And then we go into week 7 where we are talking of some of the defects associated with ECM. We will look at basics of electrochemical drilling some associated ECM you know processes or electrochemical machining processes like drilling, grinding, stream drilling, electrochemical grinding etcetera. We will carry out again thermal you know packages and material associated material removal in 8 weeks 8 where we discuss the 3 principle thermal processes that is EDM, EBM, and LBM. We of course, do on one side some mathematical modeling related to estimation of MRR through external circuits as is very commonly visible using you know EDM process. We will try to estimate using you know a correlation between the power loss on one hand and then trying to regress it to the actual experimental what EBM process through the application of the Buckingham pi theorem. We will also try to look at laser beam machining and try to do thermal model on one side and then get into the mechanics of the material removal based on the thermal model and try to estimate what is the material removal rate.

And then week 12 would be dedicated mostly to some of these initiatives in the nanomanufacturing as well as the self-assembly related you know context. So, typically all information which will be covered here will give you fairly good idea of these processes and the domains into which it can be activated and their outcomes or their achievements in terms of surface integrity, the smallness of the parts that you can create and also the fine tunability into engineering systems as I have been advocating earlier. So, I think I will like to finish you know my lecture here with the set of books and references which I will often on use, and this will of course be typically the fundamental part of the course. I am going to refer to a lot of journals, journal papers to illustrate the recent research work which has come out based on some fundamentals which are given through these books and references. So, I wish you good luck in this course, and then in the next lecture, we will start taking up the microfabrication and the silicon you know processes in great detail. Thank you very much again. Have a good day. Thank you.