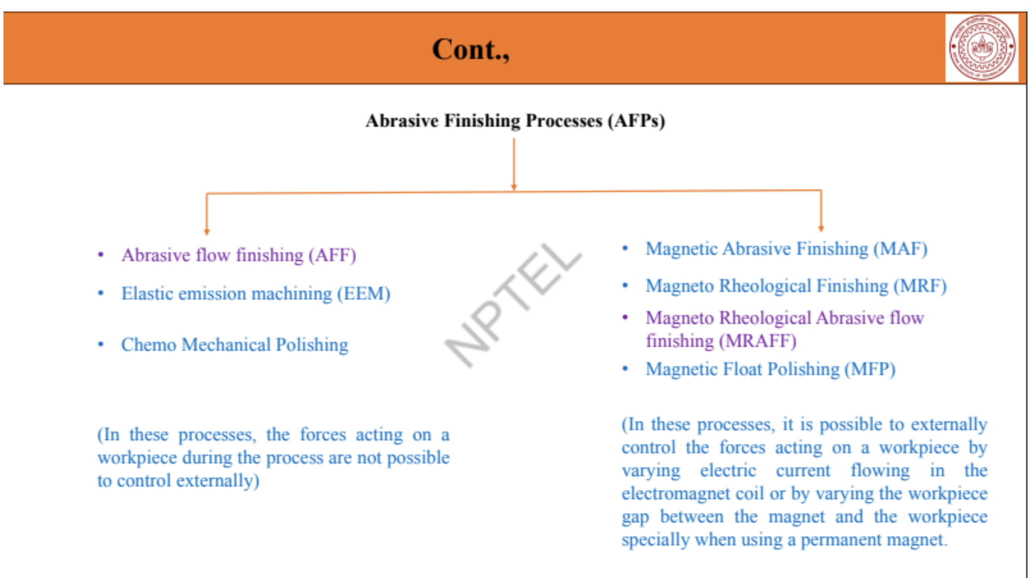
Advanced Machining Processes
Prof. Shantanu Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur
Week - 11
Lecture – 28
Advanced Finishing Processes

Hello and welcome to this advanced machining processes course. Today we will be talking about advanced finishing processes. There is a variety of requirements of finishing that is being posed on the final component after the machining processes which are conventional or non-conventional are executed on surfaces. This finishing is highly needed for its ultimate integration into engineering assemblies. So, let us look at today what are the options which are available in the finishing domain. There are some very critical processes which are used for finishing or fine-tuning of the surfaces which are generated out of all the machining process.

And basically, some of these advanced finishing processes use the latest technology for doing very high precision finishing because particularly in implants, biomedical implants also when we talk of silicon processes or electronics we do need an ultra-flat surface. And therefore, traditional finishing processes in those kind of situations like grinding lapping, honing, etc. may have some limitations. So, the first limitation can be that the part geometry itself is 3D geometry and it is probably very complex to have these processes designed for 3D geometry. The second of course is that the parts are highly miniaturized.



So, when we are talking of removing very very small ultra-small portions of materials from surface of parts itself which are very miniaturized then what do you do? So, you have to find out ways and means to actually have a more accurate you know or a more precise or a more focused process which will do finishing operations on the surface. So, the finishing forces in traditional finishing processes are quite sort of average in nature. So, they are very less controllable and therefore traditional finishing process cannot be used to achieve a high level of the surface finish. And the prime requirement therefore of nano finishing is to finish gently on the surface with very good location specificity where the finish needs to reach. And for most of the nano-finishing processes which are using abrasive particles either suspended or held in various viscous fluids or medium.

Again fluid particles which will change the apparent viscosity of the medium to change because of the line up with external actuation forces like magnetic fields etc. There are carbonyl iron particles which are mostly used for that purpose. And then also magnetorheological beads as change of viscosity with the function of external actuation. All these properties together can determine the reach of the finish and also the specificity of the finish on certain surfaces which are ultra-small in general. So, the processes that we are going to read which will give these kind of effects are for example the abrasive flow finishing AFM, the magnetorheological finishing and then the magnetorheological abrasive flow finishing which are the different variants of such targeted processes.

These processes have the amenability of you know finishing 3-dimensional surfaces extremely complex contours etc. which we will get to know in few minutes. So before proceeding let us actually look at some of the nitty-gritty of the array values which are obtainable and the kind of a workpiece materials which we are talking of when we do comparison of finish obtainable by different finishing process. For example, if I look at grinding the ultimate array value achievable is somewhere around 6.2 microns you know to a few 0.025 microns. In lapping processes, it is about 13 to 750 nanometers. Then when we do AFM the abrasive flow machining with silicon carbide abrasives, and we do so on hardened steels we get about 15 nanometer you know precision of the array values. We have magnetic abrasive finishing processes where again on stainless steel surfaces one is obtained about 8 nanometer finish. Again, with cerium oxide and MFP processes working on silicon nitride for example one gets again 4 nanometer finishes.

So there are other techniques also for example the magnetorheological finishing iron beam machining for example where we can go as high as about 0.1 nm almost the atomic level specificity root mean square. Now having said that as technologies evolve when you get higher and higher level of finishes of course the problem that one sees is the uniformity of finish across the surface. You are talking of a very big surface, and you are talking of small finishing effects. So, integrating similarity behavior over the whole surface becomes sometime challenging in that sense.

Now when we talk of the abrasive finishing processes in general you classify them on one category as you know the abrasive finishing, the elastic emission machining, the chemo-mechanical polishing. In these processes the forces acting on workpieces during the process are not possible to control externally. So, there are no fields or any other effects which could actually do the control of such processes. On the other hand, there are certain other processes like magnetic abrasive finishing, magnetorheological finishing, MRAF, rheological abrasive flow finishing or even magnetic float polishing where in these processes it is really possible to control the forces acting on workpieces by varying either electric current which is leading to some kind of a you know actuating an electromagnetic coil and varying the magnetic field. And in that manner or you can also vary that with a permanent magnet where the coming into the magnetic field of the whole ensemble may actually change the viscosity and become harder, the fluid becomes harder in certain areas.

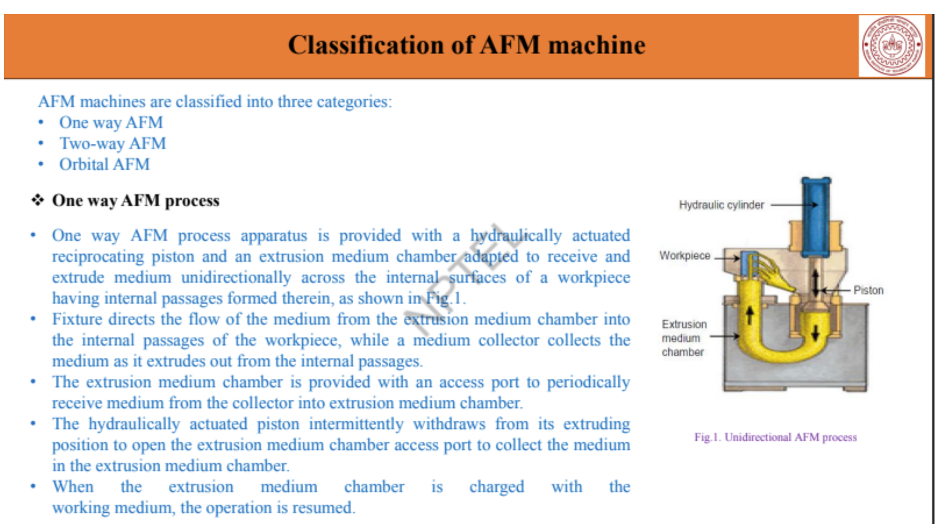
So these are the actuable kind of finishing processes. Now having said that with this kind of classification let us move ahead on the abrasive-based nano-finishing process without external control of finishing forces that is the first category of the processes. So, the abrasive flow finishing techniques were developed you know way back in 1960s by Extrude Horn Corporation. AFM can do many operations including pollution deeper parts internally then create through holes, intersecting holes, calibrate fluid injection nozzles to a specific flow rate. It is very important that in all engines whether it is IC engines or diesel engines or even the internal you know the jet engines there is a requirement of injection, fuel injection.

You know you can have either a carbureting device to do that or you can also have a just you know electronic injector do that job. But again, there is an orifice and venturi which is needed for such kind of flows to happen which are very small and so therefore, surface finishing becomes a very critical need in such devices. Now method to radius difficult to resurfaces like intricate geometries can be provided through these flow finishing processes. They can produce RA as good as about 50 nanometers for a deeper operation or as small as about 0.2 mm radius edge 0.025 mm to 1.5 mm that is how sizes of achievable radii for chamfering etcetera can take place using these processes. This processes are widely used in finishing complex shapes particularly in profiles. A key component of AFM processes include the following you have a particular machine which provides either a one-way flow of the abrasives or a two-way flow or an orbital flow as I will illustrate just in a short while. They do contain tooling’s where there can be drill bits, fixture plates, fixture, piston, cylinder which are able to guide the pressure. The pressure wave is responsible for shifting the flow of the abrasive within capillaries or venturis of smaller sizes and therefore, you have to route the pressure in appropriate manner.

Then of course, you have another component the abrasive medium which is also very important because this is what does the job of removal. The abrasive has to be pressurized to very close to a surface through a medium which is otherwise quite viscous it is like thick paste or even sometime like you know sort of high viscosity like you know putty where the abrasives are kind of carried as a plug as a flow plug operating within different channels because of extreme pressures. Now, the process input parameters of course, are the pressure of extrusion that creates an effect of flow of this very dense thick slurry containing the abrasive particles. There is also a relation to the number of cycles of flows which means thereby that if the cyclic process you know induces this translation of the abrasives coming close to surfaces you can actually either make it a to and fro effect or even you know single directional unidirectional effect. But again, how many cycles are used in the machine to finally achieve a fixed array value is a parameter.

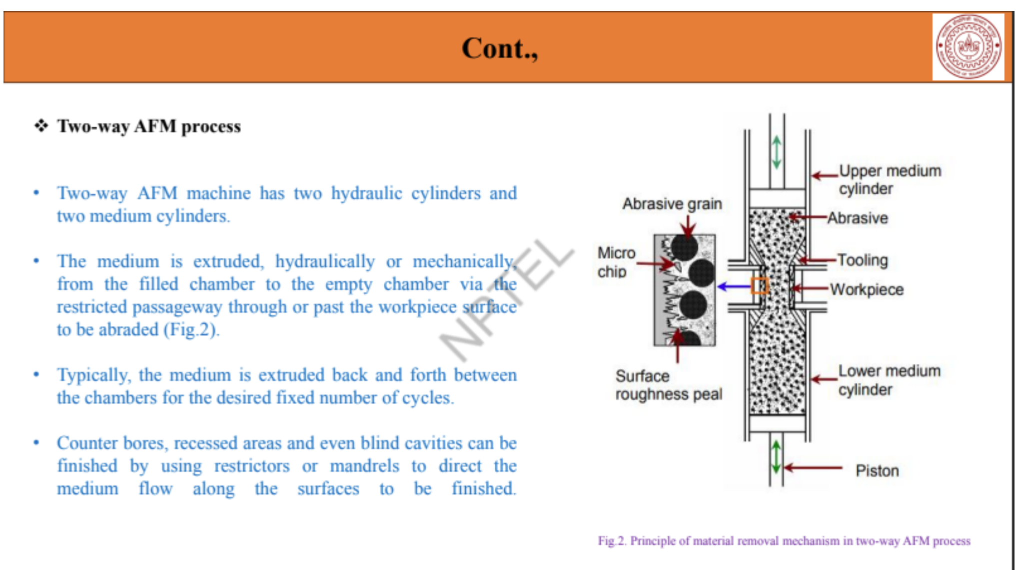
You have grid composition and type, the tooling type and the fixture design. So, these are different process input parameters for the AFM the abrasive flow machining process. I am going to classify AFM now as one-way, two-way and orbital AFMs. Now, in the one-way AFM as you can see here the apparatus is provided with a hydraulically actuated reciprocating piston and an extrusion medium chamber which is adapted to receive and extrude a dense material medium containing the abrasive and containing the slurry around it in a unidirectional manner. And that goes across the internal surfaces or a geometries which need to be fine finished of workpieces.

And they can have internal passages like you can see here small passages coming out you know through which the flow is being pushed or even larger passages for example, like this you know. So, there are various intricacies that you put or push the abrasive medium. And the fixture directs the flow of the medium from the extrusion medium chamber into the internal passageway of the workpiece. And then of course, there is a medium collector which kind of collects the medium as it extrudes out from the internal passages. So, you essentially having a one-way throughput where the abrasives are pressurized close to the small crevices or sizes and the remove material, and that removed material is caught up in the very thick slurry which transports it and it extrudes out of the system taking all the you know material removed from the passages.



The extrusion medium chamber is provided with an access port to periodically receive medium from collector into the extrusion medium chamber. And the hydraulically actuated piston intermittently withdraws from its extruding position to open the extrusion medium chamber access port to collect the medium in the extrusion medium chamber. And when the extrusion medium chamber is charged with the working medium the operation is again resumed. So, in that manner, you have a one-dimensional flow resulting in material removal. The same thing can be slightly varied by a two-cylinder or a two-piston approach where you can actually rather than moving it unidirectionally make the flow to happen in a two and fro manner across the workpiece which needs to be you know fine finished.

The medium is extruded here hydraulically or mechanically from the filled chamber to the empty chamber via the restricted passageways through or past the workpiece surface to be abraded. But then again you can do this in a two-and-fro manner where it is not just a single directional flow of cut, but you know cutting happens in both directions of flow of the medium. So, typically the medium is extruded back and forth the chamber and desired number of cycles are fixed which will give a certain array value after you know implementation of all the cycles. The counterbores, recessed areas and even built cavities blind cavities can be finished by using restrictors or mandrels to direct the medium flow along the surfaces to be finished. So, that is a two-way AFM process.



Now, there is also an orbital AFM which is shown here you know in this process the workpiece is precisely oscillated in two or three dimensions within a slow-flowing pad of compliant elastic plastic AFM medium. You can see this compliant pad you know which is similar to the shape that you are wanting to sort of carve on the surface. And in the orbital AFM the surface and the edge finishing are achieved by rapid low-amplitude oscillation of the workpiece relative to the self-forming elastic plastic abrasive polishing tool. There is a small thin section which is filled through the flowing medium and the tool is a pad or a layer of abrasive-laden elastic-plastic medium, but typically higher in viscosity and more you know in elasticity or elastic properties. So, the orbital AFM concept is generally to provide translational motion to the workpiece.

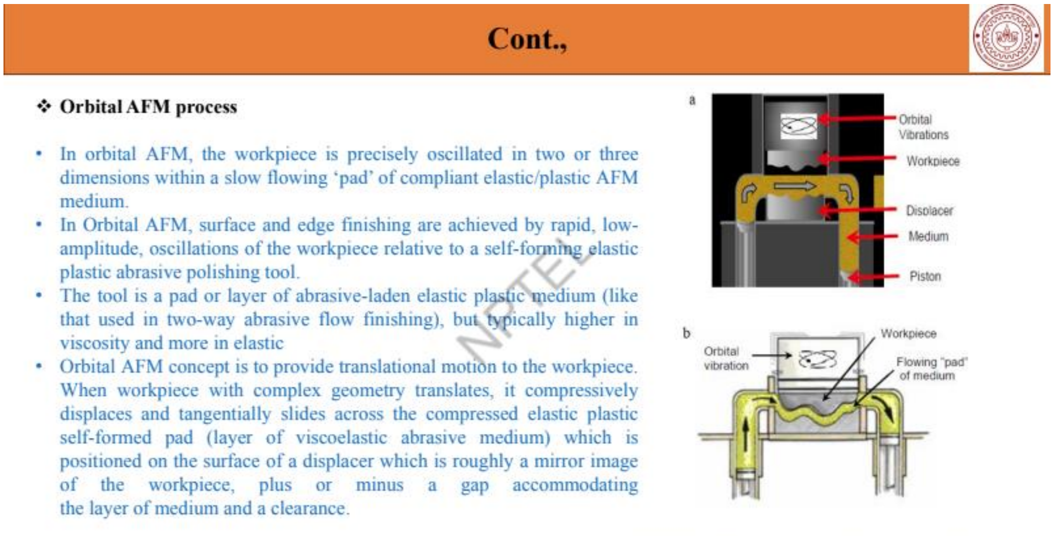


Fig.3.Orbital AFM (a)before start of finishing, (b) while finishing

When workpiece with complex geometry compressively displaces and tangentially slides across the compressed elastic plastic self-formed pad which is positioned on the surface of a displacer which is roughly a mirror image of the workpiece plus a certain gap you know accommodating the layer of the medium and the clearance. So, you essentially trying to build a negative and trap the medium within the negative and the surface and giving orbital motion to the workpiece surface in this manner. So, that is about the orbital AFM polishing tool. So, we will now discuss the process input parameters and their influence on the output responses particularly the average roughness value and the material removal rate also. So, experimental investigations which have been carried out very strongly suggest that there are very marked effects of process parameters, parameters like for example, extrusion pressure, number of cycles, viscosity of the medium, nature and type of the abrasive concentration and the particles you know the size of the grains for example, the even the output responses vary quite a bit the average roughness as well as the material removal during all the combinations of some of these input parameters.

Now, let us sort of define certain observations in this category one is that when the medium is suddenly forced through restrictive presages there is of course, ability of the medium to have an apparent change in the viscosity more so because you are working on it you are you know adding shear stresses to the material medium and the energy generally of the system or the whole you know process goes up because of which there is a sort of a apparent viscosity number which comes up you know into existence. Also, it has been observed very clearly by many researchers that significant material removal is observed as the thickness is intentionally changed if the medium is thicker than the material removal will be higher and the amount of abrasion during AFM depends on the design of tooling of course, the extrusion pressure, the medium viscosity, the medium flow volume all these different parameters have a dependency on defining the nature and type of you know roughness's that are obtained. Now, all these parameters ultimately change the number of particles interacting with the workpiece and the force acting on the individual grain which results in either more indentation or more numbers of indentation together and that kind of gives you a reason for estimating what is the flow rates or the metal removal rates. So, a higher volume of medium flow would generally increase the number of interacting abrasive grains as intuitively one can reason, and hence more abrasion should typically take place if the flow is higher the number of you know the cycle speed is higher. Now, as the number of cycles also depend on the velocity of the medium during a given time period, therefore, intentionally if you alter the velocity the number of cycles of course, will increase per unit time and it will result in quick finishing processes.

Also, the flow pattern of the medium depends on its way that it exits the workpiece we call this slug which comes out after the finishing process of course, it is having dislodged material. So, there is some increase in the volumetric compaction the mass per unit volume, and other things of the medium which comes out. Now, the medium flow pattern of course, would depend on the flow speed of the output flow again the medium rheology after passing through such you know small crevices and passage sizes and you know if you stress out the fluid more it is obvious that the overall internal energy would increase because then it has to go through severe you know interlayer stresses as it goes through smaller and smaller channels. So, the medium viscosity effect is kind of most significant property which determines the material removal and perhaps it is a dominating factor to even the extrusion pressure because sometime the medium viscosity plays a dominant role in all these finishing processes. So, it is also reported that major change of the surface finish is observed after finishing for only a few cycles and after that whatever is done is more or less redundant perhaps you can think of it that the surface gets flattened and the ability to have new exposed surface goes at a reducing rate as it gets flattened, and you know more and more flattened or more and more you know planar or planarized.

So, if you look at the application side of AFM the many, they find lot of places including aerospace industry, medical, electronics, automotives, diem molds you know parts of manufacturing activity. This right here is complex automotive engine part which shows all the crevices and the pipes, and you know a very good surface finish requirement which is there on the complex automotive part. Now, obviously, among the automotive sector, it is probably good to mention that the demand for the AFM kind of processes are increasing among all the car manufacturers. It is able to finish automotives and medical parts greatly. Again, for turbine and engine components and parts related to gas turbines also we can have very good range of application of the AFM process.

Again, dies and molds if you compare again the surface preparation of dies and molds is a very important issue. Sometimes you have to have secondary processes like sometimes you know let us say processes like EDM and ECM are used quite heavily to get surfaces which are free of stresses. But then again because of the recrystallization effect etc. and the perhaps melting recrystallization kind of layering which happens it is important to planarize that layer because it is random formulation and therefore increase in roughness is obvious. So, therefore all dies and molds typically have to go through such kind of finishing processes.

Now, the AFM process abrading medium confirms to the passage geometry complex shapes, and it can finish very complex you know complicated shapes also very easily. Overall, there is a reduction in the production cost, there is enhancement in surface uniformity, improved die performance and you know extent of life of dies and molds are severely you know changed because of such finishing processes. The smoother the better you know in terms of whatever they are producing on the surface the output of the pressing processes also change significantly on a good surface finish of the dies or die surfaces. The original 2-micron RA EDM finish and EDM is a process which is by and large used in all dies as you perhaps recall because of its die-sinking behavior.

It is improved to almost 0.2 microns with a stock removal of the whole EDM cast layer to an extent you know of 0.025 mm per surface that is how important you know this whole flow finishing processes as hybrid or assistive to the primary removal process like EDM etc. Now, when we talk of the aerospace industry again it is in great need of improved surface quality, it is in need of enhanced high cycle fatigue strength of the materials these are all dynamic parts rotating at very high rpm and therefore, it is important to sort of monitor and keep a watch on the fatigue as well. Again, this is optimized combustion and hydraulics which needs the surface topology to be perhaps well defined. It can also be used sometime to increase air flows by making ultra-smooth surfaces where there are hardly any wall frictions or skin friction effects of you know moving gases within these materials and also for extended component life you prefer AFM processes.

Similarly, in the medical industry one can eliminate the surface imperfection where dangerous contaminants can reside particularly when we talk of implants there is a lot of protein fouling issue which is depending highly on the surface morphology. So, if the morphology can be taken down to less than 100 nanometer is always in the advantageous because sometime the rate at which the adsorption kinetics would happen on the surface is a morphology-driven phenomena that can be controlled. So, you have improved also when you are talking of tissue integration and other things you sometime deliberately need roughnesses where let us say the bones are to be surrounded with the tissues and the cartilages and the growth becomes better if the roughnesses are tailored or customized. So, we do improved functionality of the part as well and good durability and reliability of the components when we talk of implants through these kind of finishing processes. Of course, you have enhanced uniformity cleanliness of surface extended component life these are some issues which are the obvious benefits of AFM process abrasive flow machining process.

Let us now look at the other side which is where you can tailor the external forces control the external forces through some you know associated change in the environment. One such change in environment could be magnetically assisted there can be a change in the magnetic field and because of which there can be a possibility of the medium viscosity the apparent viscosity to suddenly change because of such changes. And such processes are called magnetorheological abrasive flow finishing processes we otherwise you know call it with condensed form MRAF. Now, this is a very new precision finishing process of course, what it basically means is it is a combination of both the abrasive flow machining as you have studied in detail in the earlier you know few slides and the magnetorheological aspect of the finishing fluid as such which is combining strength wise you know to the AFM process and this has been developed for of course, nano finishing of parts even with complicated geometry for a wide range of industrial applications. Now, mechanisms of material removals in MRAP processes typically we have to study it in you know close observation.

In MRAP processes the magnetorheological polishing fluid is typically used as a medium as I told you earlier it has properties of changed viscosity on some actuation magnetic field actuating magnetic field externally. The MRPF the medium that is there for doing the finishing is actually a combination of you know the carbon iron particles CIPs and abrasive particles in some kind of a medium like grease or paraffin liquid which is the base material or the base medium and then very well stirred and well mixed.

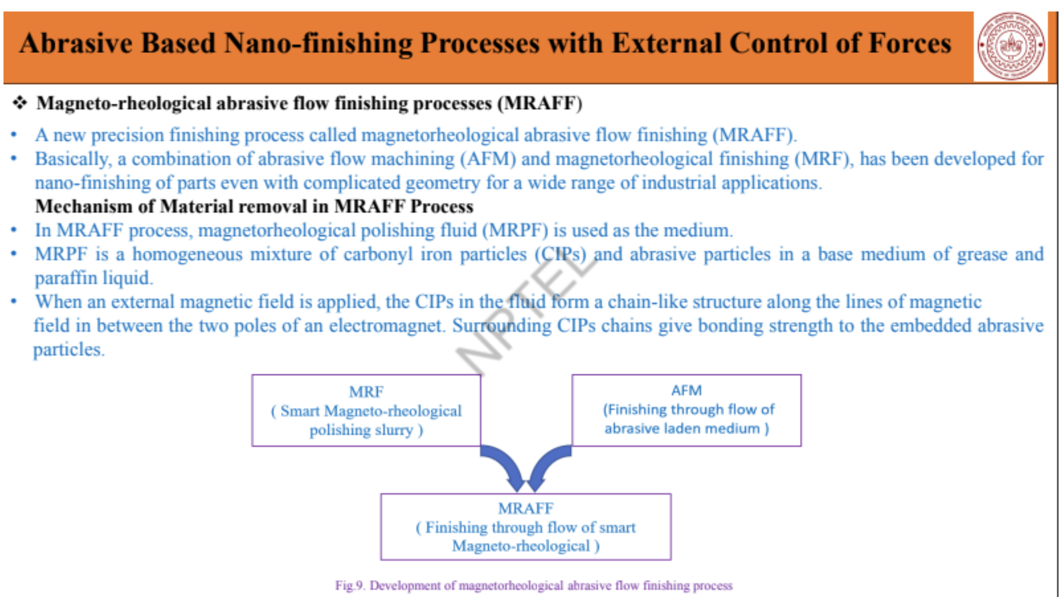
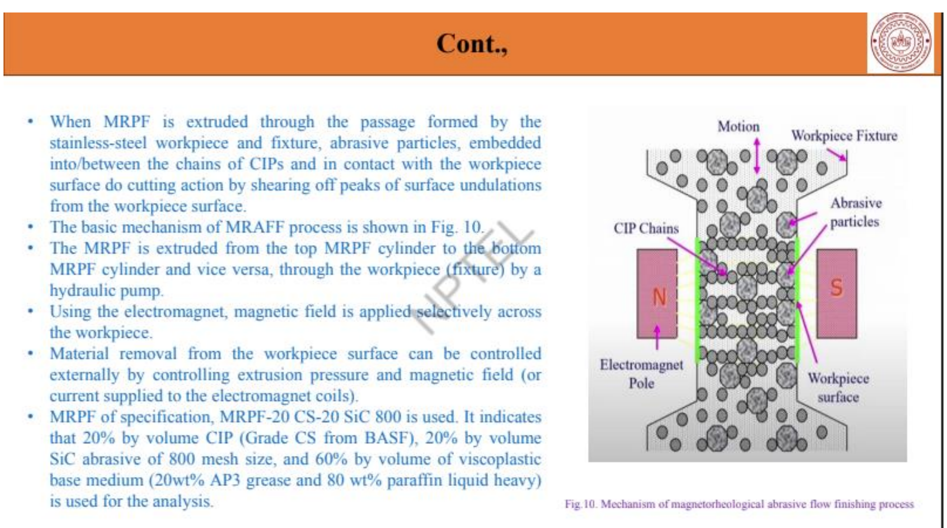


Fig.9. Development of magnetorheological abrasive flow finishing process

The main advantage of MRPF is pertaining to the fact that when we are subjecting it externally to certain definition magnetic definition you can align the carbonyl particles along with the abrasives in a linear manner depending on the field lines. And so therefore, wherever the lines pass through or cut through the medium there is a tendency of the apparent viscosity of that region to slightly go up because of such alignments. And depending on the strength of the magnetic field the magnetization of the material and the various other phenomena associated with the field losses you know or let us say the susceptibility, the magnetization ability you can have a range of viscosity is obtainable through such external actuation.

The advantage of this process would be that when the actuation goes away for example, the magnetic field is eliminated you will suddenly see the change of state of viscosity back to normal C. So, there is a relaxation effect which happens when there is no magnetic field. And so, you can actually now you know define area-wise on the surface where you would like the apparent viscosity to go up and where you would really not like the apparent viscosity to go up. And in a way that is the basis of you know even customizing the material removal rates at various zones of interaction of the MRF with respect to the surface in question. So, that is the sort of you know basic scheme of events here.

You have the smart magnetological polishing slurry MRF mixed with the power of the AFM which is finishing through flow of abrasive lead, and you know medium. And then combining together it gives you finishing through flow of smart magnetological fluids. Let us look at schematically what is going on and try to understand the material removal rate a little bit through first principles. Now, in this particular effect as is illustrated here there is a fixed magnetic field because of these two north-south pole permanent magnet. And when the magnetological polishing fluid is extruded through the passage which has the magnetic field and perhaps the fluid goes past the stainless-steel workpiece surface and the fixture.



There is cutting action on the workpiece surface by the shearing of peaks of surfaces which are coming projected into the path of the medium you know from the workpiece surface. So, therefore, if there is some as you can see here there is some very small roughness on the surface here where peaks are coming up and down on the you know path of flow. As the abrasives are pushed through this densification process in this particular zone, particularly the magnetic field zone you see suddenly there is an organization effect of the CIPs which leads to a zone of apparently a higher hardness or higher viscosity. And this gives you a sort of pushing effect pushing outwards effect and the cutting forces of the abrasive grains which pass in this manner to shear off those small distractions coming off the surface. They are suddenly increased because of such kind of outward pressure which comes because of the change in the viscosity because of line and lining up of the magnetic material.

So, one could change this scheme from a permanent magnet to an electromagnet where you can use the electrical field again to have variable magnetic fields and therefore, typically all MRAFs today are done using electromagnets. And the material removal from the workpiece surface is controlled externally again by controlling the extrusion pressure on one hand and the magnetic field on the other. And so, you have now rather than a single parameter controlling the material removal you have multi parameters including pressure as well as field both combined together you know. So, that is how this kind of process works. Now, the MRPF has perhaps specifications you know things like MRPF20, CS20, SiC800.

What it indicates is the percentage by volume that each component has in the slurry. For example, this particular number here 20 means what is the volume percentage of the CIP. The grade of the CIP is perhaps CS. This is generally obtained from BASF. There is a company which is specialized in making CIP particles.

It is also the company which typically used to give this for all the hard drives and displays, hard drives and you know gramophone records and others and it is a long-standing history. You have again a certain percentage of the abrasive in this case it is the silicon carbide abrasive which has 20 percent by volume again. And then this number here mentions the mesh size of the SiC. It is about 60 percent of course, because the 20 plus 20 is occupied by the CIP and the abrasive. So, the remaining 60 percent is the visco-plastic medium, the base medium which is perhaps 20 base percent loaded AP3 grease, and 80 percent loaded paraffin liquid which creates you know the sort of a blended fluid for the medium to carry all this or suspend all this in different percentages as mentioned.

So, this is how you specify MR fluids and now one can look at you know the typical machine that is used the schematic that is used for doing the magnetological abrasive flow finishing experiments. So, you do have solenoids here controlled through DC power supplies. You have a bottom MRPF cylinder, and you have another top cylinder and there is a two-way flow through

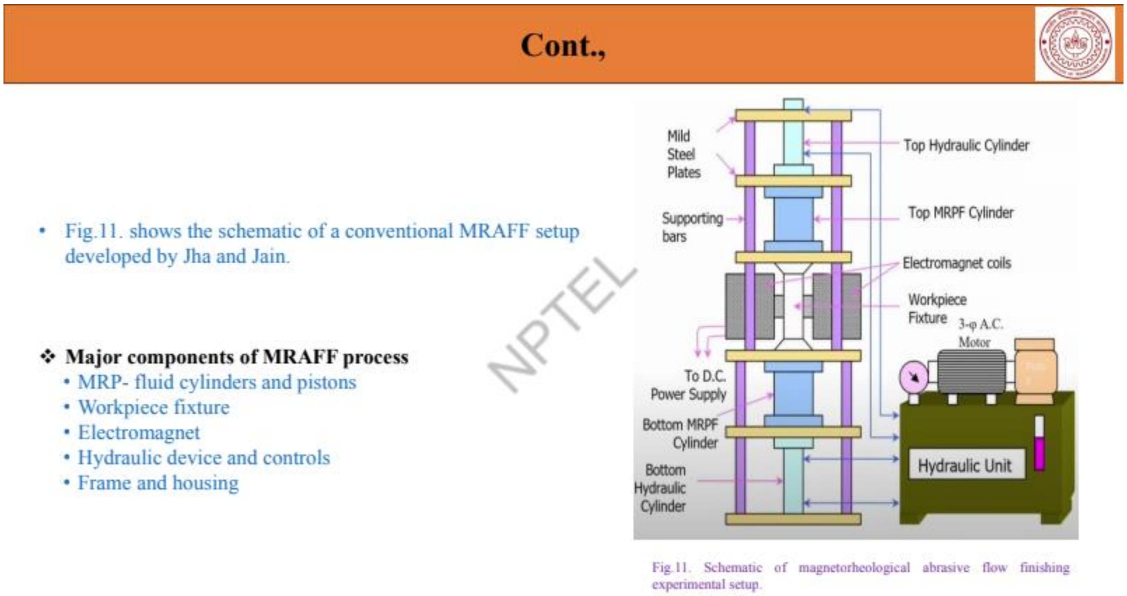


Fig.11. Schematic of magnetorheological abrasive flow finishing experimental setup.

two hydraulic rams on either sides. There is a bottom hydraulic ram and there is a top hydraulic ram to apply the 2N4 pressure for the medium to flow between the top cylinder to the bottom and vice versa. And the workpiece really is put across this particular electromagnetic coils, whereas the flow comes the coil actuates and it generates you know substantial amount of material removal.

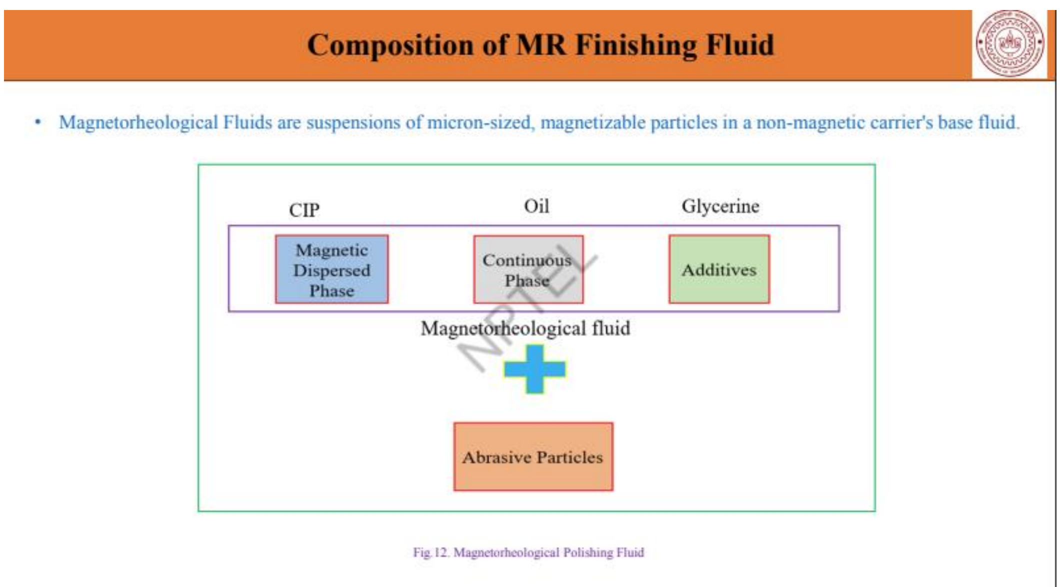


Fig.12. Magnetorheological Polishing Fluid

Major components of MRAP process include the fluid cylinder and piston, includes workpiece fixture, electromagnet, hydraulic device and controls, frame and housing, and so on so forth. So, therefore, in a nutshell the composition of the fluid is again three components the CIP, the oil which is the grease and the paraffin wax and some additives which are there plus the abrasive particles and the magnetological fluid. And they are suspensions of micron size, the magnetizable particles in a non-magnetic carriers-based fluid. So, that is how MR finishing fluid is realized.