

Advanced Machining Processes
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Lecture 25
Magneto-Rheological Finishing (MRF)

Welcome to the course on advanced machining processes. Today I am going to discuss a finishing process that is named as magneto rheological finishing abbreviated as MRF process.

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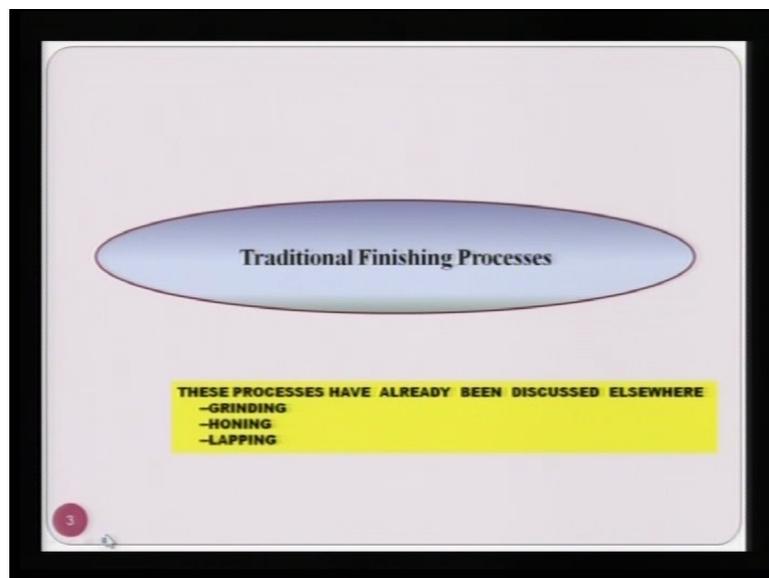
The contents of this particular talk are as follows. Traditional finishing processes, magneto rheological fluid, magneto rheological finishing process, process parameters of MRF process, applications of MRF process.

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Traditional finishing processes, we have already seen at some other places in some other course three well known traditional or conventional finishing processes. These processes are known as grinding, honing and lapping. All the three processes have their constraints.

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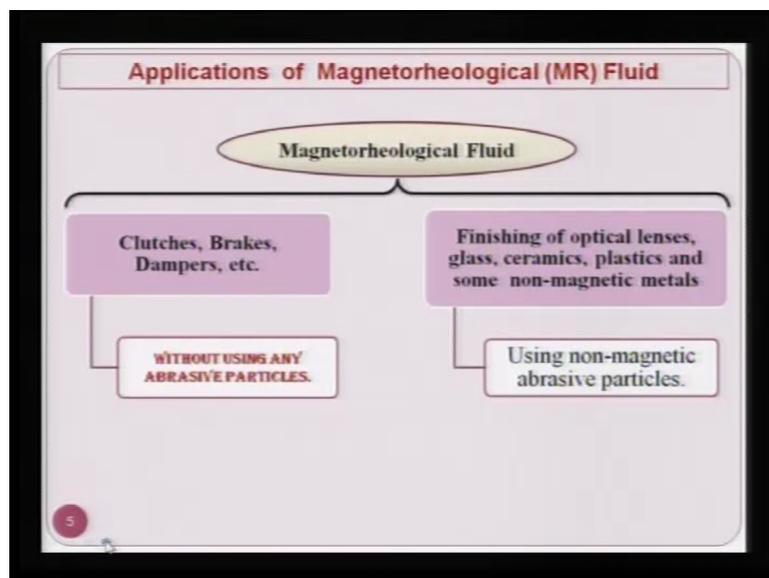
Especially grinding has the limitation while it can be applied for flat surfaces or cylindrical surfaces. Second another problem with grinding is that large amount of heat is generated because of which thermal stresses are there that are produced in the ground component. Thermal cracks are created and another important point is this process cannot be used for a complex shaped geometry. Honing gives a good surface finish, not very large amount of heat is generated but it is limited to the cylindrical external and internal surfaces.

Against some other shapes can be machined but not a very large variety of shapes can be machined by this. Same is true as long as limitations are concerned with lapping. Lapping is a very good process commonly used but it is very good for flat surfaces. It can give good surface roughness value that is very low surface roughness value. But for complex shaped components it cannot be applied.

Also to some extent in honing and lapping some very fine thermal cracks may be developed which we will not be discussing here at this point of time. Magneto rheological fluid, this magneto rheological finishing process consists experimental setup and the medium which is known as magneto rheological fluid or magneto rheological polishing medium. Now this medium is a burn with acts as a tool in finishing process.

Applications of magneto rheological fluid, now magneto rheological fluid without having the abrasive particles is also used for many other applications rather than only magneto rheological polishing. When we are using this fluid for polishing purposes we add up the abrasive particles which act as the finishing tool as we will see here.

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The magneto rheological fluid has the applications in the clutches, brakes, dampers, etc. The important point to note here is that the fluid does not contain any abrasive particles. But on the right hand side if you see this magneto rheological fluid is used for finishing of optical lenses, glass, ceramics, plastics and some non-magnetic metals. Now important point here to note is that this fluid is using non-magnetic abrasive particles. These particles include alumina Al_2O_3 , silicon carbide SiC , it can be diamond particles also.

But in this particular talk we are going to discuss is the application of magneto rheological fluid in the field of finishing. And this process when using magneto rheological fluid along with the abrasive particles we call it as magneto rheological polishing fluid or MR polishing fluid also. And in this talk I am going to discuss only magneto rheological finishing process which is used MR polishing fluid as the tool. The constituents of MR fluid are as follows. Magnetic particles, abrasive particles, carrier fluid and stabilizers.

As you can see here in this particular table the magnetic particles maybe carbonyl iron powder or also known as carbonyl iron particles, electrolyte (electro) or electrolytic iron powder and iron cobalt alloy. As you can see on the first column on this particular table.

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MR fluid constituents			
The main constituents of MR polishing fluid are			
Magnetic particles	Abrasive particles	Carrier fluid	Stabilizers
Carbonyl iron powder (CIP)	Cerium oxide	Water	Glycerol
Electrolyte Iron powder	Diamond powder	Oil	Grease
Iron - cobalt alloy powder	Aluminium oxide		Oleic Acid
	Silicon carbide		Xanthan gum
	Boron carbide		

Then there are various kinds of abrasive particles which are added to this particular fluid. Cerium oxide, diamond powder, aluminium oxide, silicon carbide, boron nitride, etc. The major constituent of any MR polishing fluid is the carrier fluid and it make a lot of difference as long as performance of the finishing process is concerned. In case of certain workpiece materials it is always recommended to use water as the carrier fluid while in some other cases oil is recommended as the (calie) carrier fluid.

Now when you are mixing up magnetic particles and abrasive particles in the carrier fluid what you are going to get is that these magnetic particles and abrasive particles will settle down at the bottom because they have higher density compared to the carrier fluid. So we need what is known as stabilizer and there are various kinds of stabilizers which are used in

magneto rheological polishing fluid. It may be glycerol, grease, oleic acid or xanthan gum. One of these is used depending upon the requirement.

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MR fluid constituents			
The main constituents of MR polishing fluid are			
<ul style="list-style-type: none"> • Magnetic particles • Abrasive particles • Carrier fluid • Stabilizers 			
Magnetic particles	Abrasive particles	Carrier fluid	Stabilizers
✓ Carbonyl iron powder (CIP)	Cerium oxide	Water	Glycerol ✓
✓ Electrolyte iron powder	Diamond powder	Oil	Grease ✓
✓ Iron-cobalt alloy powder	Aluminum oxide		Oleic Acid ✓
	Silicon carbide		Xanthan gum ✓
	Boron carbide		

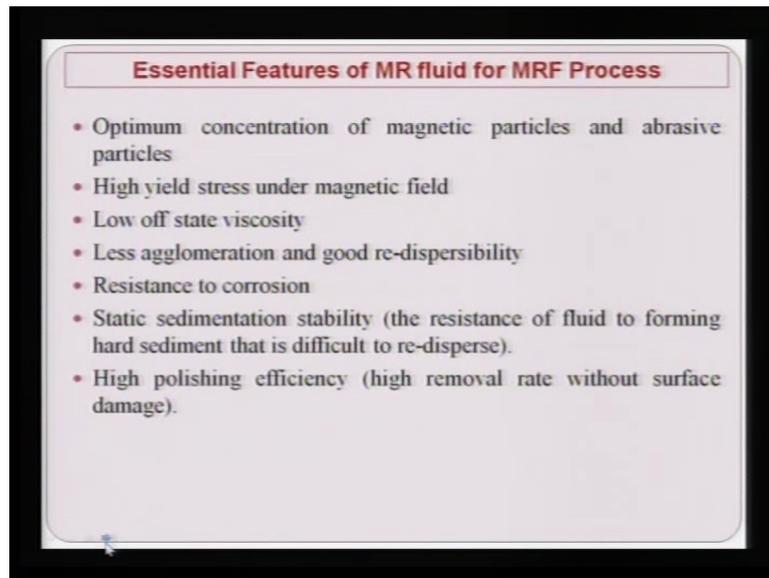
Essential features of MR fluid for magneto rheological finishing process. Optimum concentration of magnetic particles and abrasive particles is very important. If the percentage of these two constituent is very high then definitely the efficiency of the finishing process is going to go down. High yield stress under magnetic field, here we are applying the magnetic field and the fluid is always subjected to the magnetic field.

So whatever are the properties are of MR polishing fluid, without the application of magnetic field and with the application of (na) magnetic field are going to be very different from each other. Low off state viscosity means the viscosity of the fluid without the application of the magnetic field. Less agglomeration and good re-dispersibility should be there. The particle should not get agglomerated otherwise they are going to affect the performance and quality of finishing.

And once the magnetic field is no more, then the particle should get dispersed quickly. And resistance to corrosion. Static sedimentation stability that is the resistance of fluid to forming hard sediment that is difficult to re-disperse. That is what I mentioned earlier in case of point 4 that in static conditions they should be static.

That means sedimentation should not take place otherwise the properties of the fluid are going to change and that will not give the proper finishing. High polishing efficiency that is high removal rate without surface damage.

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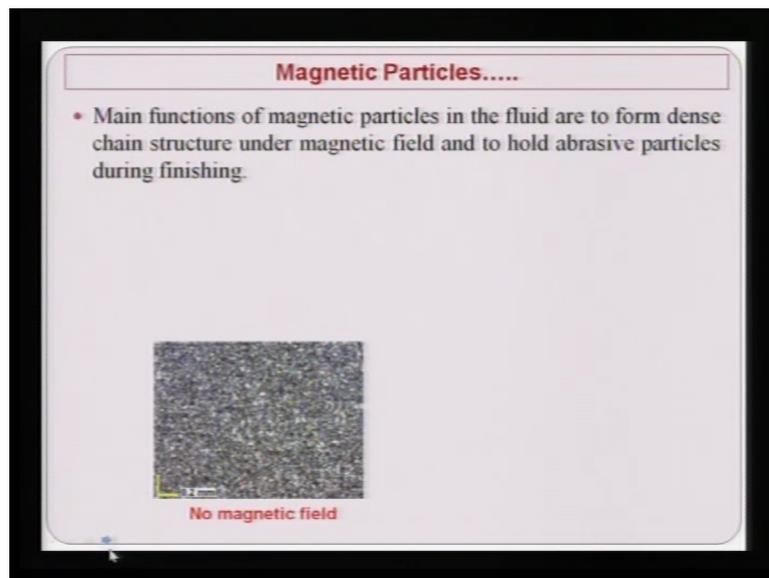


Now apart from this high material removal rate we as the manufacturing engineer are always concerned with the high finishing rate because in finishing processes finishing rate is more important than really material removal rate. Because in finishing processes objective is to achieve the desired surface finish without any defect and in the lowest possible time. So here objective is not to remove the large amount of material from the workpiece surface, rather to finish and achieve the desired surface finish in the minimum possible finishing time.

Magnetic particles, main functions of magnetic particles in the fluid are to form dense chain structure under the magnetic field and to hold abrasive particles during finishing process. This is very important and once the abrasive particles are held by the magnetic particles chains then this acts something like a very soft grinding wheel where in which the bonding material is holding the abrasive particles, then finishing is being done.

But in this particular case once the fluid is out of the magnetic field zone then it will shatter and it will convert in the form of the easily flowing liquid. You can see here in the figure there is no magnetic field and white color they indicate the alumina and blackish color they indicate the iron particles or carbonyl iron particles. And they are uniformly distributed across the fluid.

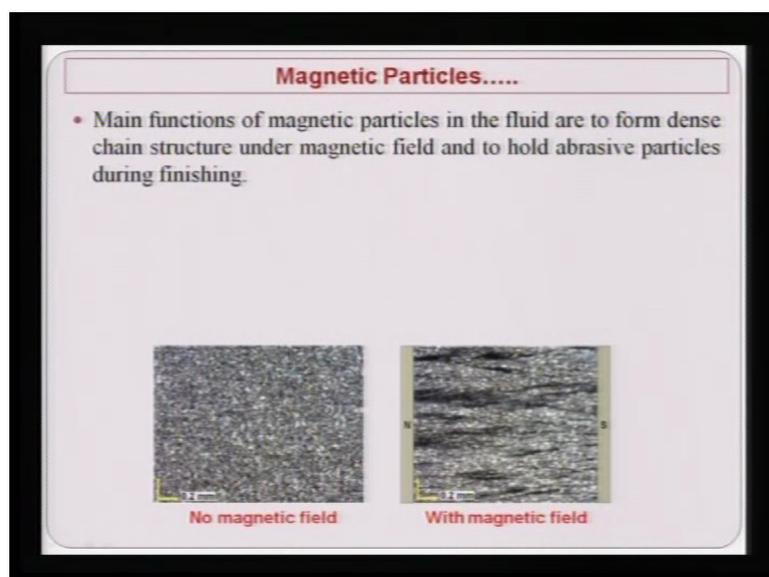
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But when you apply the magnetic field you can see the same fluid with the same distribution of iron, abrasive particles, carrier fluid and stabilizer they are forming the chains. As you can see on the right hand side and the abrasive particles are held either within the chains or between the chains.

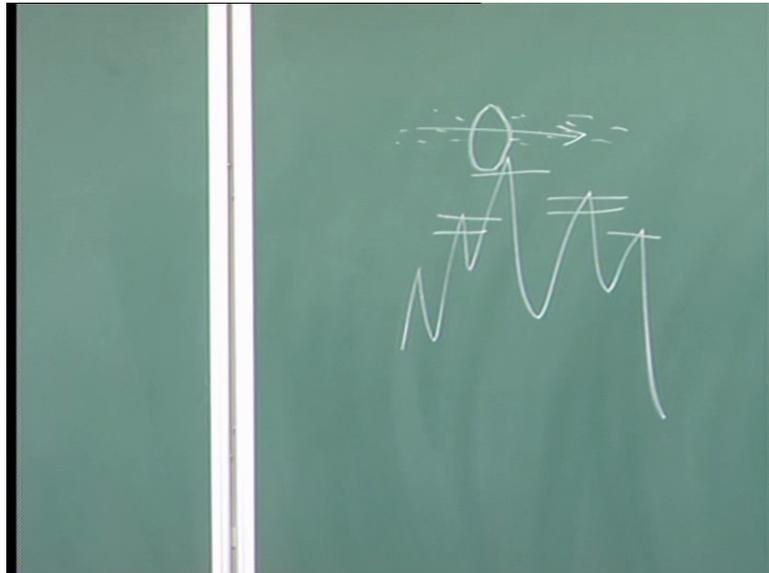
And when there is a relative motion between this particular abrasive particles in the chain and the workpiece surface then these abrasive particles that act as a tool and they remove the material from the piece or the workpiece surface. And that is how you keep getting better and better surface finish.

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I will just show you here something like this and this is the abrasive particle which is being held by the fluid. There is a chain of the iron particles and this chain is being pushed in this particular direction due to the rotation of the wheel. Then this peak will get removed like this and the Ra value, RMS value will keep decreasing.

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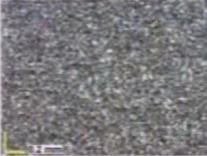


Without magnetic field, magnetic particles are dispersed randomly in the MR fluid as shown in figure 1 a and under the influence of magnetic field, magnetic particles are aligned along the magnetic flux lines. As you can see here is the north pole, here is the south pole so this is the direction in which the chains are being formed. As you can clearly see that chains are there and in between the chains some abrasive particles are being held. In between the chains or within the chains.

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Magnetic Particles.....

- Main functions of magnetic particles in the fluid are to form dense chain structure under magnetic field and to hold abrasive particles during finishing.
- Without magnetic field, magnetic particles are dispersed randomly in the MR fluid as shown in Fig. 1 (a).
- Under the influence of magnetic field, magnetic particles are aligned along the magnetic flux lines (from N-pole to S-pole) as shown in Fig. 1 (b).



No magnetic field



With magnetic field

Many types of magnetic particles are available for MR fluid preparation. As I mentioned earlier you can use carbonyl iron particles although carbonyl iron particles are very expensive. Electrolyte iron powder, iron cobalt alloy powder, etc. CIPs are made by chemical vapor deposition, decomposition of iron pent-carbonyl.

While electrolytic iron powder is prepared using the electrolytic or spray atomization process and CIPs are more preferable compared to others because it is magnetically soft, chemically pure and high saturation magnetization. That is 2 point 1 Tesla at room temperature which is really very high value of saturation compared to the saturation value for any other iron or magnetic particle.

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Magnetic Particles

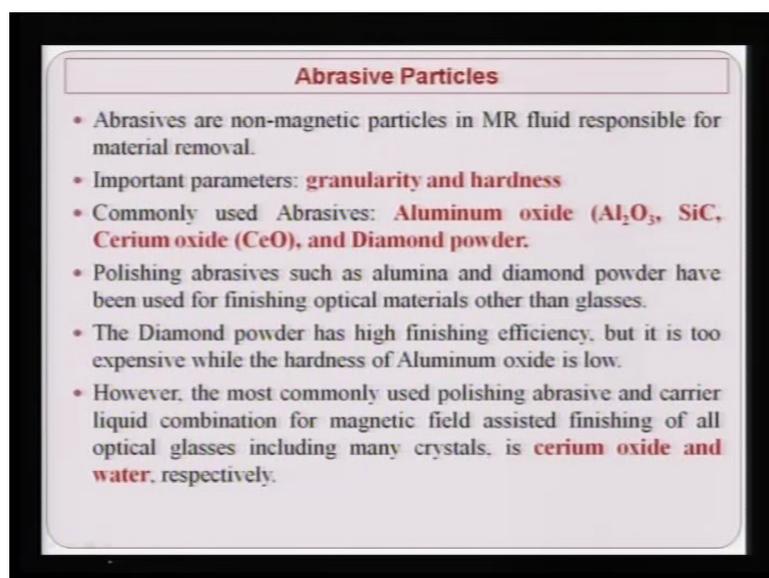
- Many types of magnetic particles are available for MR fluid preparation:
 - > Carbonyl iron particles (CIPs).
 - > electrolyte iron powder.
 - > iron - cobalt alloy powder, etc.
- CIPs are made by chemical vapor deposition (CVD) decomposition of iron pentcarbonyl.
- While electrolytic iron powder is prepared using the electrolytic or spray atomization process.
- CIPs are more preferable compared to others because
 - > it is magnetically soft.
 - > chemically pure, and
 - > high saturation magnetization (2.1 Tesla at room temperature).

Abrasive particles are non-magnetic materials in MR fluid responsible for material removal. As I have mentioned earlier that these are the abrasive particles which really remove the material from the workpiece while chain or chains of iron or carbonyl iron particles they just act as the bonding material in the grinding wheel and they hold these abrasive particles and when there is a relative motion between the abrasive particles in the workpiece surface, material is removed in the form of microchips or nanochips depending upon the finishing conditions.

Important parameters, granularity and hardness of these abrasive particles which makes the difference as long as finishing rate is concerned. Commonly used abrasive particles are aluminum Al_2O_3 , silicon carbide SiC , cerium oxide CeO and diamond powder. Other abrasive particles also can be used depending upon their availability, cost and the requirement of the process. Polishing abrasives such as alumina and diamond powder have been used for finishing optical materials other than glasses.

The diamond powder has high finishing efficiency but it is too expensive while the hardness of aluminum oxide is low. So diamond particle can be used but quite expensive. So one has to see the application then only diamond should be used as the abrasive particle for finishing purposes. However the most commonly used polishing abrasive and carrier liquid combination for magnetic field assistant finishing of all optical glasses including mine crystals is cerium oxide and water respectively.

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Abrasive Particles

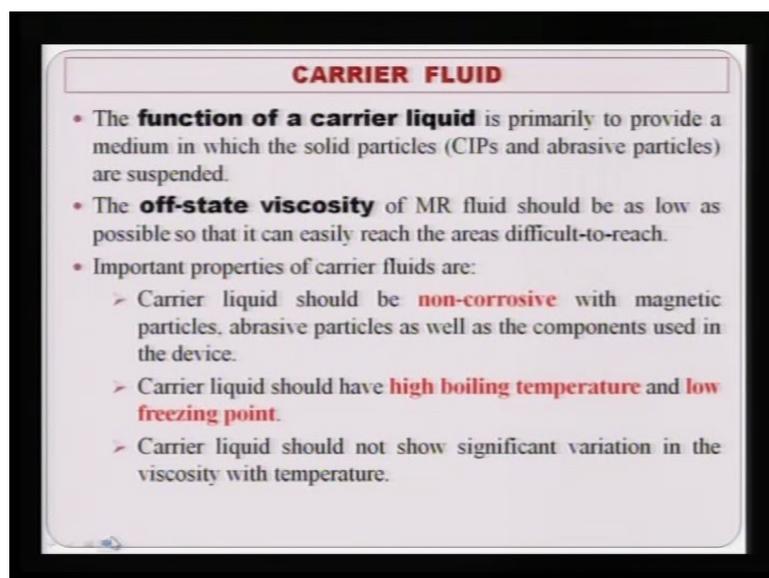
- Abrasives are non-magnetic particles in MR fluid responsible for material removal.
- Important parameters: **granularity and hardness**
- Commonly used Abrasives: **Aluminum oxide (Al_2O_3), SiC , Cerium oxide (CeO), and Diamond powder.**
- Polishing abrasives such as alumina and diamond powder have been used for finishing optical materials other than glasses.
- The Diamond powder has high finishing efficiency, but it is too expensive while the hardness of Aluminum oxide is low.
- However, the most commonly used polishing abrasive and carrier liquid combination for magnetic field assisted finishing of all optical glasses including many crystals, is **cerium oxide and water**, respectively.

The function of a carrier (flu) liquid is primarily to provide a medium in which the solid particles like (cairon) carbonyl iron particles and abrasive particles are suspended. The off state viscosity of MR fluid should be as low as possible so that it can easily reach the areas difficult to reach because wherever this fluid reaches and wherever there is relative motion between the abrasive particles and the workpiece surface, finishing will take place only in those areas.

Now if fluid is not able to reach those areas, difficult to reach, then definitely no finishing is going to take place and you will not get appropriate finished area as you want. Important properties of career fluids are, carrier liquid should be non-corrosive with magnetic particles that is the carbonyl iron particles or iron particles. Abrasive particles like alumina or silicon carbide, diamond, etc. as well as the components used in the device that is the machine or MRF machine components material.

Carrier liquid should have high boiling temperature and low freezing point because heat is generated to some extent and definitely the carrier fluid should not start boiling otherwise it will not be able to serve its purpose properly. And it should have low freezing point because at many locations the temperature or environmental temperature is low, so it should not freeze otherwise it will not serve the function for which the fluid is to be used. Carrier liquid should not show significant variation in the viscosity with the temperature.

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CARRIER FLUID

- The **function of a carrier liquid** is primarily to provide a medium in which the solid particles (CIPs and abrasive particles) are suspended.
- The **off-state viscosity** of MR fluid should be as low as possible so that it can easily reach the areas difficult-to-reach.
- Important properties of carrier fluids are:
 - Carrier liquid should be **non-corrosive** with magnetic particles, abrasive particles as well as the components used in the device.
 - Carrier liquid should have **high boiling temperature and low freezing point**.
 - Carrier liquid should not show significant variation in the viscosity with temperature.

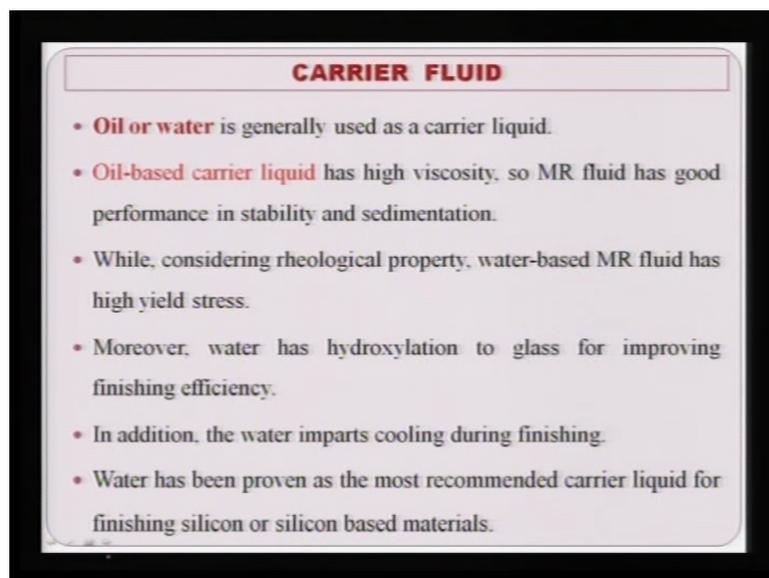
As I just mentioned the temperature is changing and with the change in the temperature the viscosity of the career fluid should not change substantially otherwise it will not remain in the

design parameter condition and if it does not remain in the design parameter condition then definitely you are not going to get the desired finishing rate and final surface roughness value. Oil or water is generally used as a carrier fluid. Oil based carrier liquid has high viscosity. So MR fluid has good performance in stability and sedimentation.

That simply means that solid particles will not be able to sediment or will not be able to settle down so easily because oil has higher density compared to the water. While considering rheological property, water based MR fluid has high yield stress compared to oil based liquid. Moreover water has hydroxylation to glass for improving finishing efficiency. In addition the water imparts cooling during finishing.

Definitely the cooling rate in case of water is higher as compared to the cooling rate in case of oil. Water has been proven as the most recommended carrier(fluid) liquid for finishing silicon or silicon based materials.

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Invariably water is used in case of silicon or silicon based material for finishing purposes because it chemically reacts and it is able to easily finish ceramics or ceramics based materials by comparatively soft abrasive particles.

Stabilizers, the stabilizer is used to disperse the magnetic particles and abrasive particles uniformly in suspension and to retard oxidation of the magnetic particles and prevent agglomeration which I have (ment) emphasized earlier also that the stabilizers are needed so that they do not permit solid constituents of the MR polishing fluid that is CIP or carbonyl

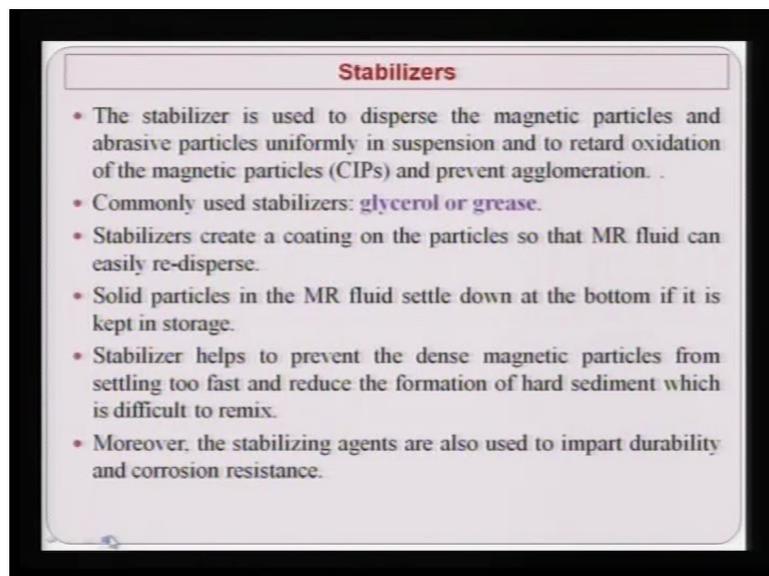
iron particles and abrasive particles. Commonly used stabilizers are glycerol or grease. Stabilizers create a coating on the particles so that MR fluid can easily redisperse.

That means due to the stabilizer it tries to minimize the agglomeration of these solid particles or powder so that they can be easily dispersed in the fluid. Solid particles in the MR fluid settle down at the bottom if it is kept in storage.

Stabilizer helps to prevent the dense magnetic particles from settling too fast and reduce the formation of hard sediment which is difficult to remix because we do not want that hard sediment should be prepared of the magnetic particles or non-magnetic particles otherwise mixing of these particles or hard (par)sediment becomes very difficult.

And one should be very careful before using these MR polishing fluid, it should be properly mixed for a good amount of time otherwise the performance of the polishing or MR polishing will not be as desired. Moreover the stabilizing agents are also used to impart durability and corrosion resistance.

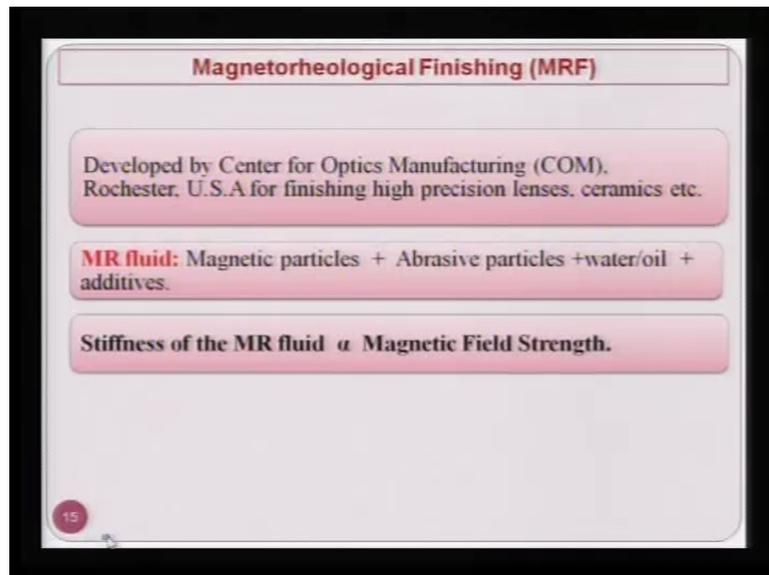
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Now let us see some details of MR finishing or magneto rheological finishing process. Here I will show you an experimental setup which has been designed and fabricated at IIT Kanpur Manufacturing Science Lab. Magneto rheological finishing, this process was developed in the beginning by the Center for Optics Manufacturing, Rochester, U.S.A for finishing high precision lenses, ceramics, etc. MR fluid consists as I have already mentioned magnetic particles, abrasive particles, water or oil as the carrier fluid and additives (())(25:04) specifically the stabilizers.

Stiffness of the MR fluid is the function of the magnetic field strength. Higher the field strength, higher is the chain or stronger is the chain being formed by the magnetic particles. And the abrasive particles will be held more strongly compared to the case when the magnetic field strength is lower.

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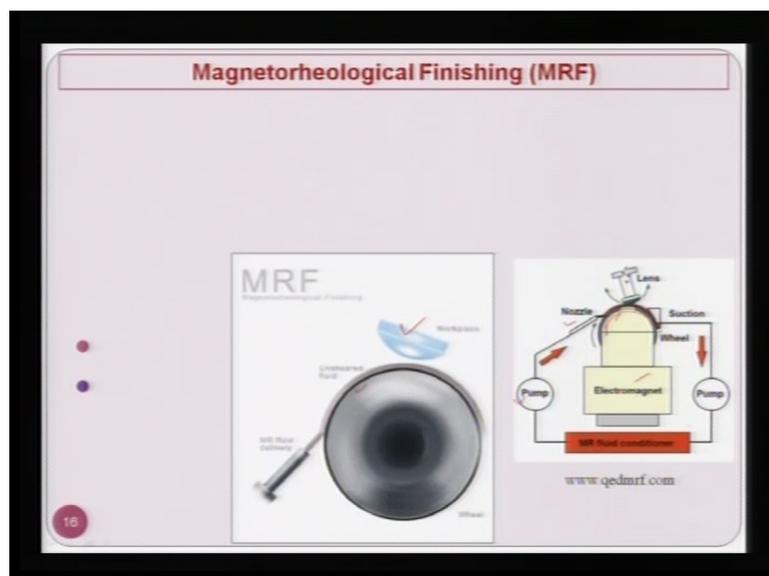
Now you can see here the function of the (am) magneto rheological finishing process. This is the lens which is to be finished and here you can see this pink color and other particles. Those pink color particles these particles are the abrasive particles and other particles are the magnetic particles. And you can see only the abrasive particles are getting in contact with the lens and it is getting finished. And you can easily rotate the lens as well as move it in these two different directions so that the whole surface of the lens is finished by this particular process.

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If you see this figure it clearly indicates what is happening in the left side figure. Here you can see here there is the electromagnet and there is the MR fluid conditioner, pump is there, this pump is pumping the MR polishing fluid to the nozzle. From the nozzle the fluid is being dispersed on the wheel. This is the wheel which is rotating in this particular direction and this fluid is coming on this and there is the electromagnet because magnetic field is there. So this fluid forms the ribbon kind of the structure on this rotating wheel.

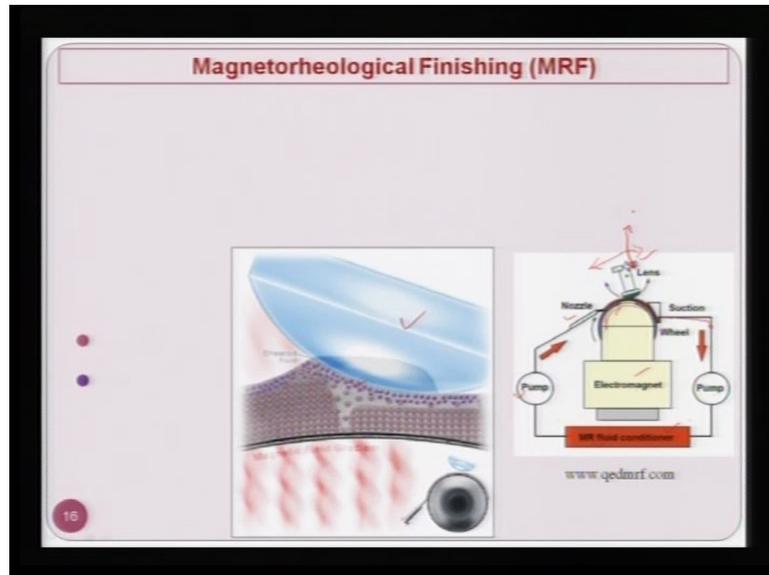
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And when it comes to the other end, there is a section and through section the fluid is taken in by the pump and it comes to the MR fluid conditioner. In this conditioner you can add some of the constituents of the MR polishing fluid as per requirement. Now this is the lens. This

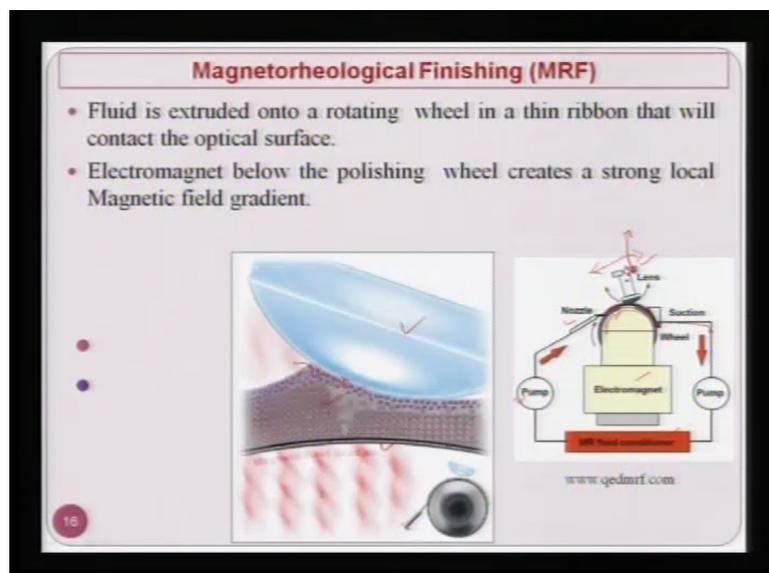
lens is rotating and you can move in this particular direction as well as in this direction so that whole surface of this particular lens is finished and you can rotate the lens at its own axis also.

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Same thing is shown over here in the left hand side in the figure. Fluid is extruded onto a rotating wheel in a thin ribbon that will contact the optical lens. You can clearly see here, this is the fluid and thin layer is there between the lens and this is the wheel and this is being extruded in this particular direction. Because of this then normal force as well as tangential force is acting on the workpiece surface through the abrasive particles which remove the material in the form of the microchips or nanochips.

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Precisely controlled zone of magnetized fluid becomes the polishing tool and that is what you can see here. This particular ribbon part acts as the polishing tool. Here this one you can see CIP shown by red color particles and abrasive particles are shown by another color particle.

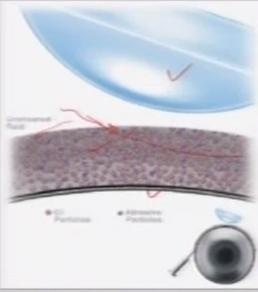
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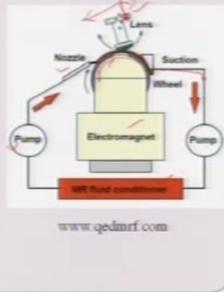
Magnetorheological Finishing (MRF)

- Fluid is extruded onto a rotating wheel in a thin ribbon that will contact the optical surface.
- Electromagnet below the polishing wheel creates a strong local Magnetic field gradient.
- Precisely controlled zone of magnetized fluid becomes the Polishing tool.

● CI Particles

● Abrasives





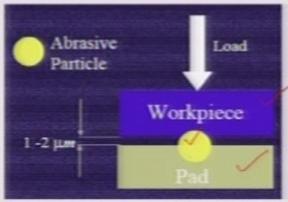
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Now lapping and chemo-mechanical polishing, we know the processes which are very good processes and extensively used in computer industries, especially the computer components and they give very good surface finish. But the rejection rate is quite large in case of CMP and as you can see here the kind of the force that is acting on the workpiece surface here, the load is acting and here is the pad and here is the abrasive particle which is finishing the workpiece surface.

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Normal Force Acting in Polishing Processes

Lapping and CMP

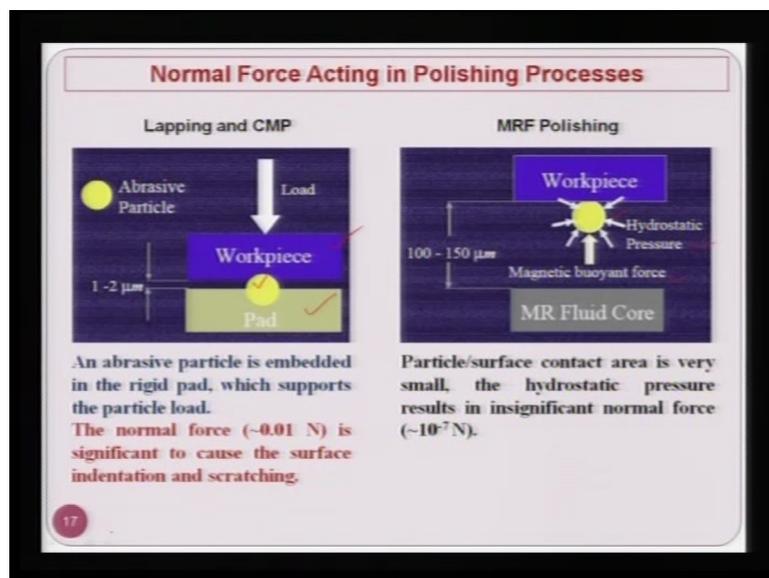


Now an abrasive particle is embedded in the rigid pad which supports the particle load. The normal force, it is somewhere point 01 Newton, is significant to cause the surface indentation and scratching. That means it damages the surface of the workpiece. Although it looks that normal force is quite low but the size of the abrasive particle is also very low.

It is the micron sized abrasive particle and so the stresses that are acting on the workpiece surface are quite large and this leads to the damage to the surface of the workpiece. That is why I mentioned that the rejection rate in case of CMP is quite high. But if you see the MRF polishing phenomena here the workpiece is in contact with the abrasive particles but abrasive particle is not in contact with any solid support kind of the things.

Rather it is the part of the MR fluid and the force being applied on the abrasive particle is through hydrostatic pressure and magnetic buoyant force. These are the two major constituents which are contributing to the normal force on the abrasive particles which is transferred to the workpiece. Now the amount of the force compared to what you are having in CMP is much lower.

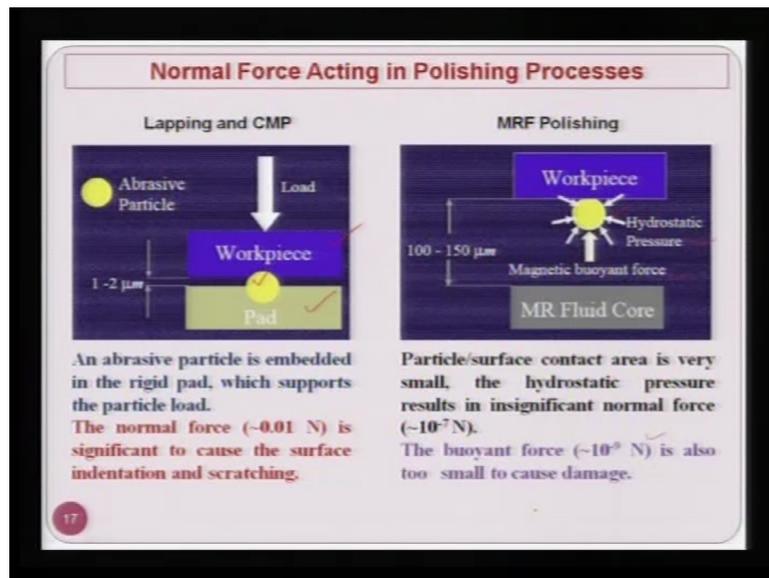
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As you can see here particle surface contact area is very small. The hydrostatic pressure results in insignificant normal force. That is 10 raised to the power minus 7 Newton while in case of CMP it is 10 raised to the power minus 2 Newton. So there is a significant difference in the magnitude of the force that is acting on the workpiece surface through the abrasive particles.

The buoyant force which is another constituent of the normal force in case of MR finishing process or MR magneto rheological fluid polishing process is 10^{-9} which is still smaller. Then the hydrostatic pressure is also too small to cause damage. That is why in case of magneto rheological finishing process the workpiece surface damage is more or less absent and stress reasonably high in case of chemo-mechanical polishing as well as lapping processes which is quite evident from this particular slide.

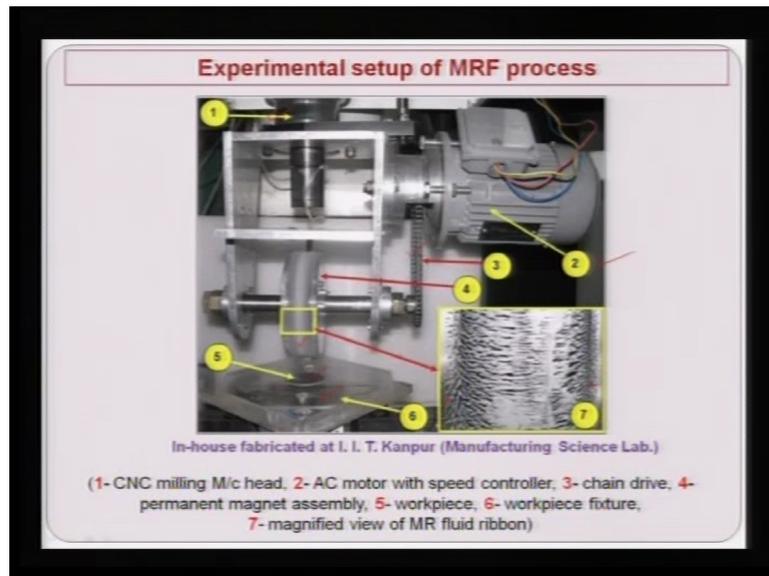
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Now this is the experimental setup. You can see it was fabricated at IIT Kanpur. Here 1 is the milling machine head. We have utilized CNC milling machine for developing this MR finishing process setup. So this is the CNC machine head. There 2 is the AC motor and 3 is the chain drive that you can see here and 4 is the permanent magnet assembly. That permanent magnet assembly you cannot see from outside. It is inside and instead of using the electromagnet, here we have used the permanent magnets.

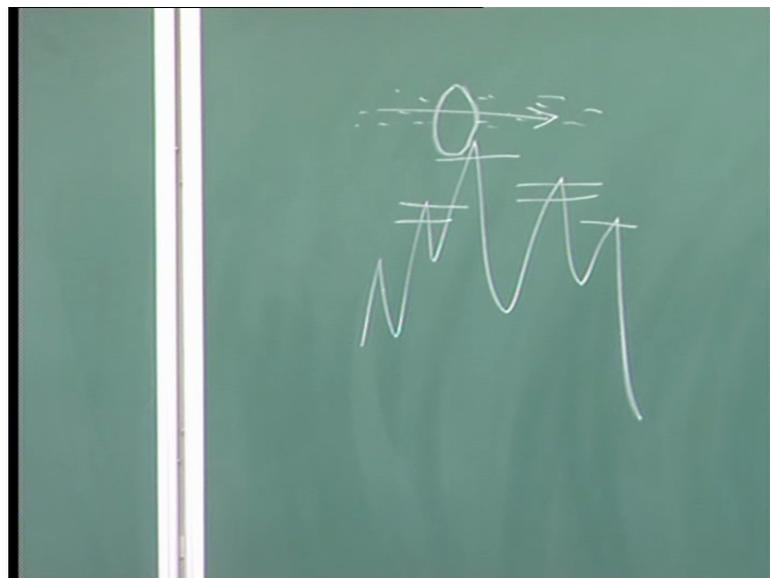
5 is the workpiece that is shown over here and 6 the workpiece fixture and 7 is the magnified view of the MR fluid ribbon. The ribbon that is being formed over here this is magnified and as you can see here these are the brushes. These are the brushes which is being formed and its strength depends upon the magnetic field strength and these brushes have abrasive particles outside, as we have seen in the video film.

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And when this abrasive particles come in contact with the workpiece surface over here then they remove the peaks, something like this one by one and the finishing is onimproving and you can get the surface finish less than 10 nanometer in this particular case easily.

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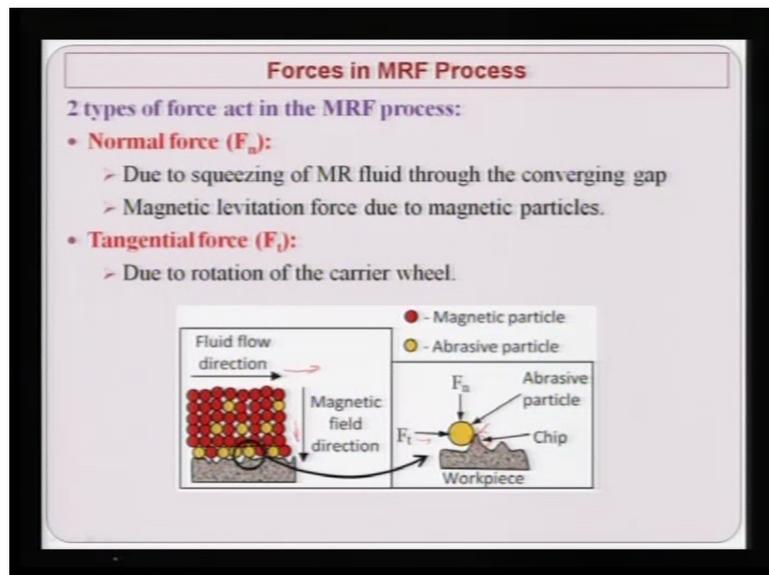


How the forces are acting? As you can see over here, fluid flow direction is shown over there in this particular direction and magnetic field direction is in this particular direction. Now when as I mentioned earlier two types of forces are acting on the abrasive particle that is the yellow color here. One is the normal force and another is the tangential or axial force. Now this is the peak of the workpiece surface.

Now when this normal force is responsible for the penetration of the abrasive particle into the workpiece surface and tangential force is responsible for remove the material from the workpiece surface in the form of the microchips. So you can see here this is the size of the microchips going to be removed and the size of this microchip will depend upon what is the normal force that is acting? And if tangential force is sufficient to remove that indented material then it is going to give you the chip.

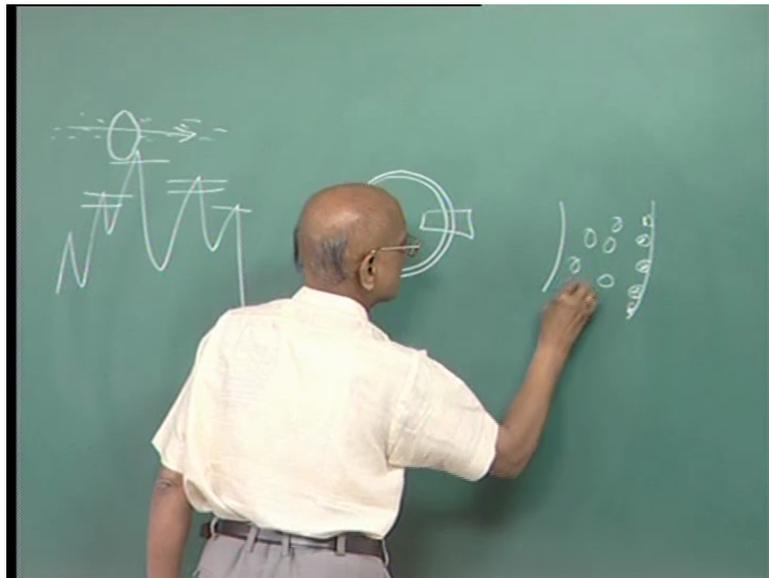
Two types of forces act in the MRF process as I have just explained to you. One is the normal force F_n and this is due to the squeezing of the MR fluid through the converging gap and second is the magnetic levitation force due to magnetic particle. And another is the tangential force. This force is due to the rotation of the carrier wheel.

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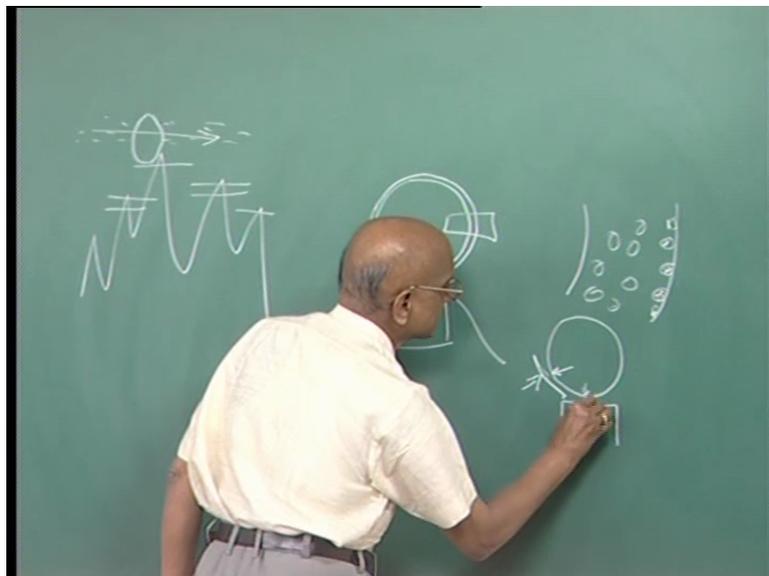
Process parameters of MRF process. Now before I proceed let me explain to you what is the squeezing force? In case of MRF process you have seen that there is a wheel which consists a ribbon and this ribbon is nothing but the MR polishing fluid consisting abrasive particles, iron particles. And if you see the enlarged view of this as you have seen in the video film it is like this. These are the abrasive particles while all other you will have the magnetic particles over there.

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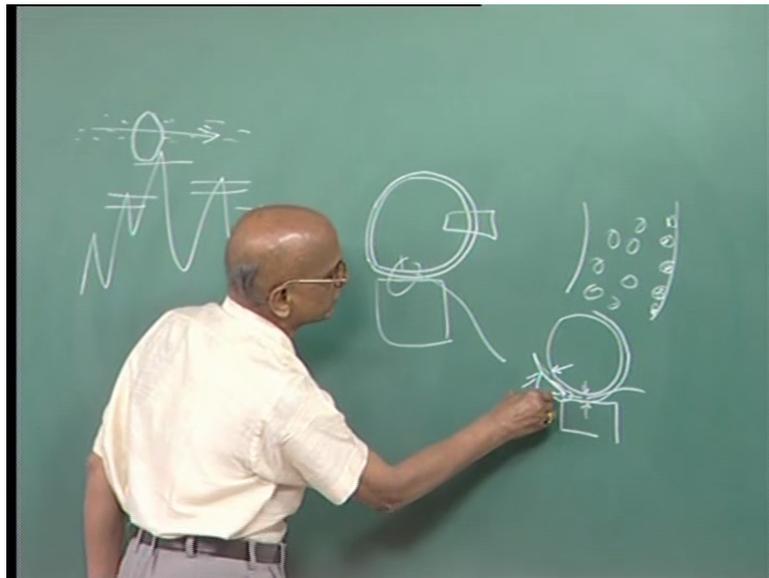
And these abrasive particles are going to come in contact with the workpiece surface. Now what you see here if you see the enlarged view of this, it is like this. This is the wheel, this is the workpiece surface and when this is there then what happens that this thickness is greater than the thickness over here.

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So this squeezing will take place. The fluid will be squeezed all over here and then it will be moving. And then this will be moving like this. When this squeezing takes place over here then this creates additional normal force on the abrasive particles.

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Process parameters of magneto rheological finishing process. Magnetic flux density that is one of the very important process parameters. RPM revolutions per minute of the carrier wheel or you can say indirectly the surface field of the carrier wheel which makes the difference. Flow rate of the MR fluid. Volume fraction of the carbonyl iron particles and abrasive particles. Size of the carbonyl iron particles and abrasive particles.

Feed rate of the workpiece that decides the relative velocity between the abrasive particle and the workpiece. And type of the workpiece material. Now there are certain parameters which depend on these finishing parameters and these parameters include material removal rate or these are also known as responses which are going to decide the performance of the finishing process.

Surface roughness, surface integrity and one thing which I will like to mention here apart from this quite important is the finishing rate in this particular case. And this finishing rate will have the unit as the removal of this peak in terms of micrometer or nanometer per unit time. So it can have micrometer per second or nanometer per second.

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Process Parameters

- **Process parameters**
 - Magnetic flux density
 - RPM of the carrier wheel
 - Flow rate of the MR fluid
 - Volume fraction of the CIPs and abrasive particles
 - Size of the CIPs and abrasive particles
 - Feed rate of the work piece
 - Types of work piece material
- **Dependent parameters**
 - MRR
 - Surface roughness
 - Surface integrity

*Finishing Rate
μm/s
mm/s.*

21

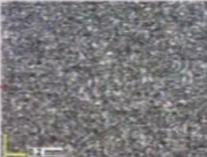
Effects of magnetic particles. As I have already explained this particular these sketches that this fluid main functions of magnetic particle are to form dense chain structure under magnetic field and to hold abrasive particles during finishing. So you can see with the application of the magnetic field it is able to form the chain structure and it is holding the workpiece within or between the chains.

Without magnetic field, magnetic particles are dispersed randomly in the fluid as shown in figure 1 a. And under the influence of magnetic field, magnetic particles are aligned along the magnetic flux lines that you can see in the right hand side figure that from north pole to south pole that is in this particular direction as shown in figure 1.

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Effects of Magnetic Particles

- Fluid Main functions of magnetic particle are to form dense chain structure under magnetic field and to hold abrasive particles during finishing.
- Without magnetic field, magnetic particles are dispersed randomly in the MR fluid as shown in Fig. 1 (a).
- Under the influence of magnetic field, magnetic particles are aligned along the magnetic flux lines (from N-pole to S-pole) as shown in Fig. 1 (b).

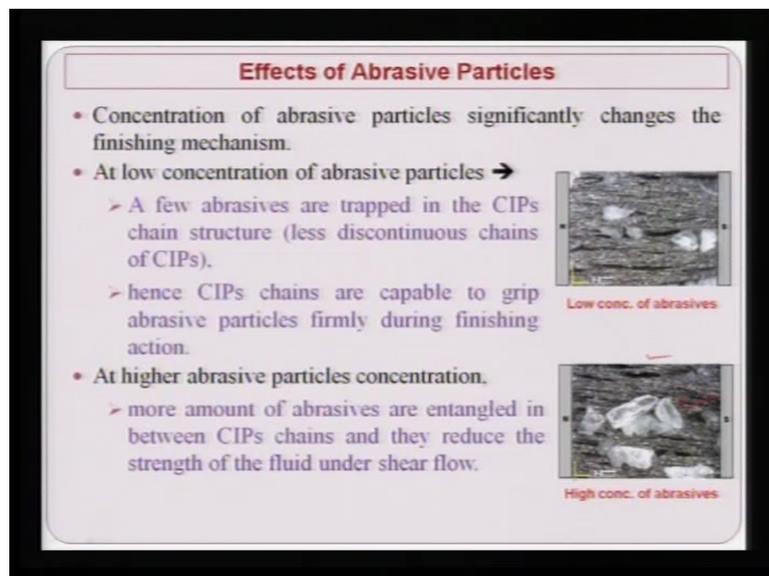
No magnetic field **With magnetic field**

And you can really simulate these chains as I mentioned earlier in this lecture with the soft bonding material of a grinding wheel. Now what is the effect of abrasive particles? Concentration of abrasive particle significantly changes the finishing mechanism. At low concentration of abrasive particles you can see here (par) particles are dispersed at different locations.

Some of the locations are without abrasive particles, some of the locations are with abrasive particles and material will be removed by these abrasive particles only and not by the carbonyl iron particles. A few abrasives are trapped in the CIPs chain structure, less discontinuous chains of CIPs are formed. Hence CIPs chains are capable to grip abrasive particles firmly during finishing process. Now when you have high concentration of abrasive particles you can see the picture over here.

So many abrasive particles get agglomerated and they are at one particular location. And this feature if it is too high may not be desirable because this may lead to the deep scratches and non-uniform finishing along the surface of the workpiece. At higher abrasive particles concentration more amount of abrasives are entangle in between CIPs chains as you can see over here and they reduce the strength of the fluid under shear flow.

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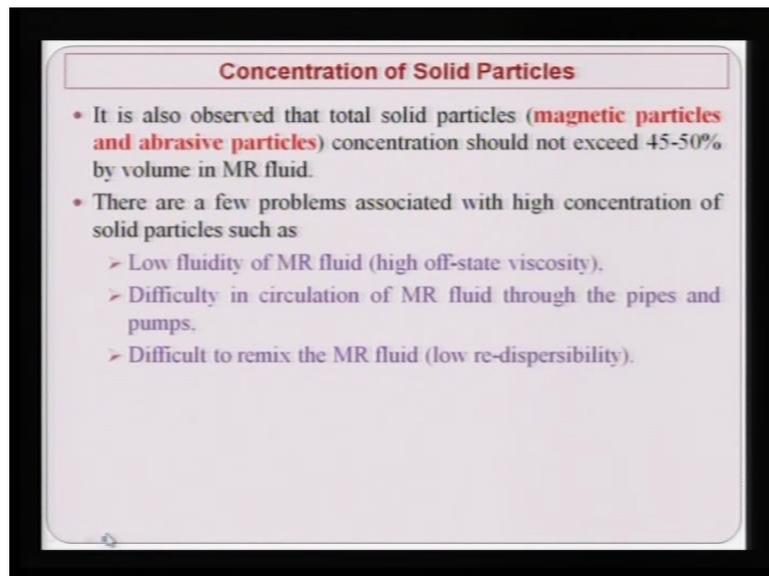


Concentration of solid particles, it is also observed that total solid particles, that is magnetic particles and abrasive particles, concentration should not exceed 45 to 50 percent by volume in MR fluid. There are a few problems associated with high concentration of solid particles

such as low fluidity of MR fluid, high off state fluidity and if high off state fluidity is there it will not be able to reach.

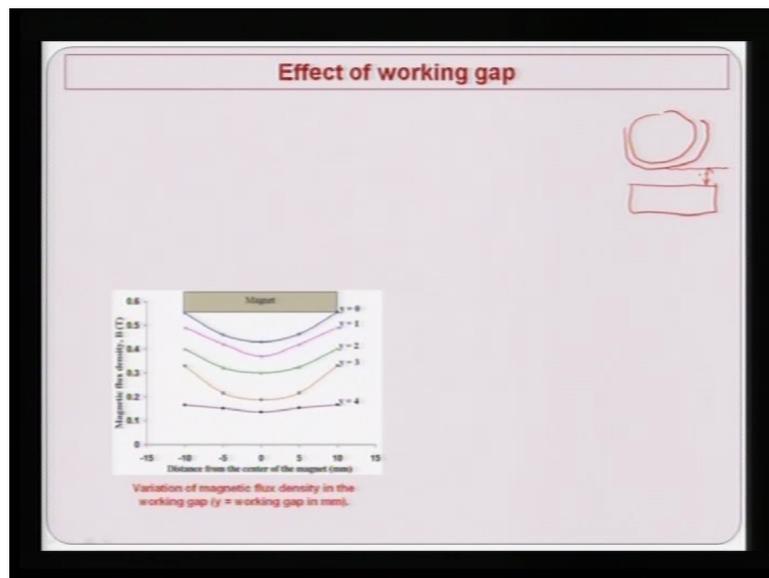
Too difficult to reach areas and you may not get proper finishing especially in case of complex shaped components. Difficulty in circulation of MR fluid through the pipes and pumps. Difficult to remix the MR fluid because low dispersibility is there.

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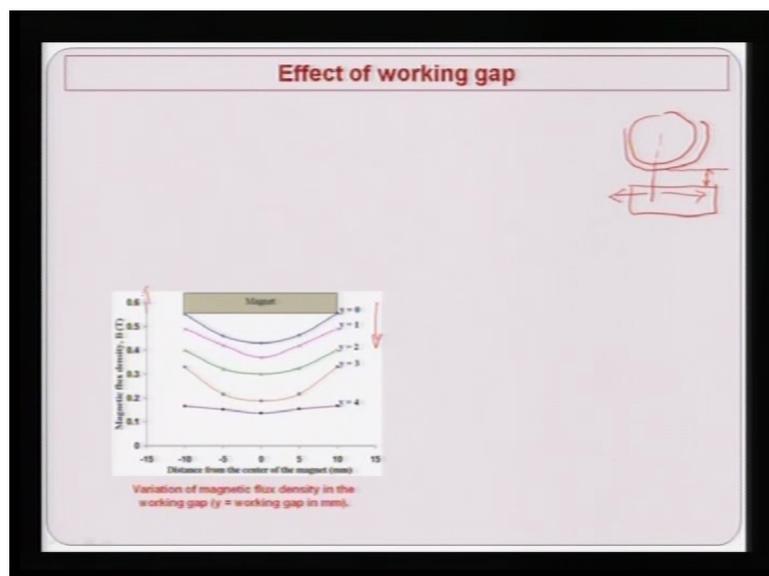
Now what is the effect of working gap? That is the gap between the lowermost level of the ribbon and the surface of the workpiece that is known as working gap as you can see over here. Suppose this is the wheel and say this is the ribbon and here is the workpiece, then the gap between the lower most part of the ribbon and the top surface of the workpiece or the surface which is being finish that is known as working gap.

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Now you can see here in this particular figure the distance from the center of the magnet. Suppose here is the magnet so this is the center of the magnet. Then on one side it is negative, left side it is negative, right side it is positive. So it says distance from the center of the magnet and magnetic flux density you can clearly see that as the distance is increasing the magnetic flux density is decreasing which is obvious. So it shows variation of magnetic flux density in the working gap and y is the working gap in millimeter and that is this particular y axis.

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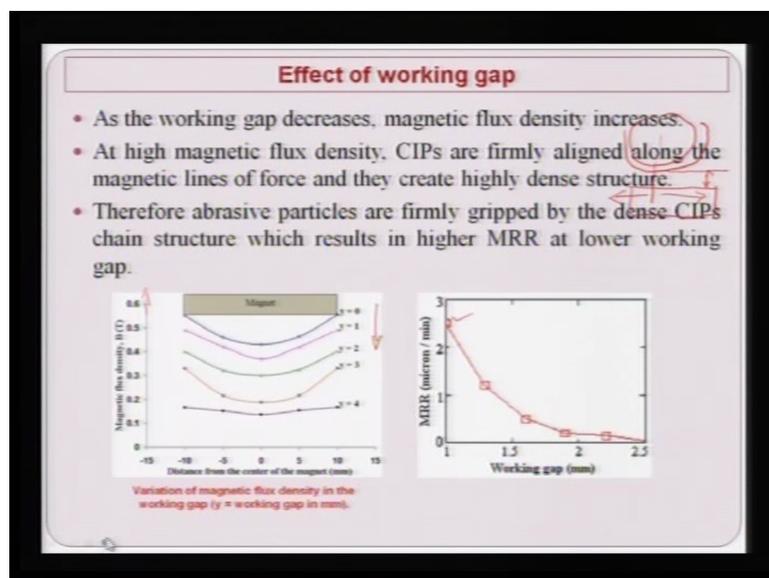


Now you can also see as the working gap is increasing, the material removal rate is decreasing and which is obvious because as the working gap is increasing you can see on the

left hand side, the magnetic flux density is decreasing. And as the magnetic flux density decreases then the holding power of the fluid to the abrasive particles will also decrease. So the fluid rather than the abrasive particles will not be able to penetrate deeper in the workpiece surface. Hence material removal rate will decrease.

As the working gap decreases, magnetic flux density increases as I have shown here. At high magnetic flux density the CIPs are firmly aligned along the magnetic lines of force and they create highly dense structure. Therefore abrasive particles are firmly gripped by the dense CIPs chain structure which results in higher MRR at lower working gap. As you can see here at the top side or left side of the figure on the right side.

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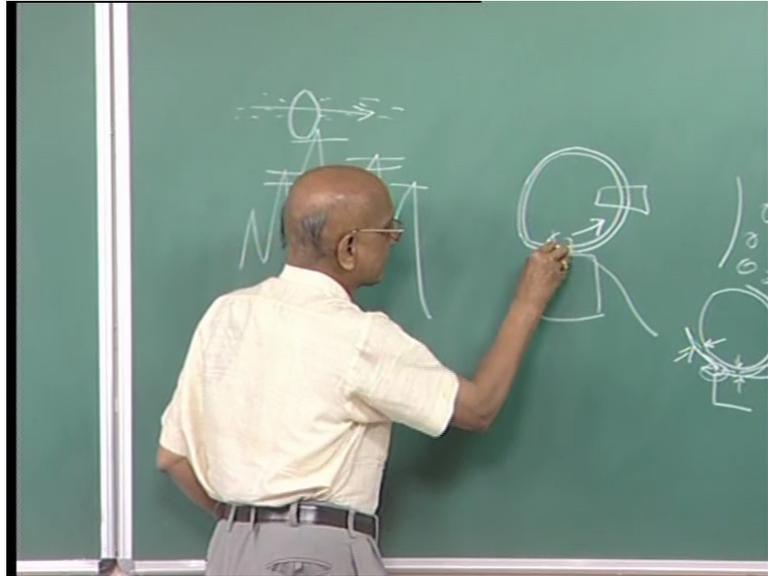


Effect of the carrier wheel speed. As you can see here this figure shows the effect of the wheel speed on (sur) final surface finish and MRR. Final Ra decreases and MRR increases with increasing carrier wheel speed. As you can see here as the wheel speed is increasing, the MRR is increasing but the final Ra value is decreasing. That is better surface finish is being achieved. It is assumed that MR fluid ribbon moves with the same speed as that of the carrier wheel speed. That is there is no slip condition exist between the wheel and the fluid ribbon.

Therefore with the increase of the wheel speed, the speed of the abrasive particles also increases. Hence the shear force applied by the abrasives on the workpiece surface also increases. That is as you can see here on the board that as this speed or the rpm of the wheel is increasing then the surfaces speed of the wheel outer periphery is increasing.

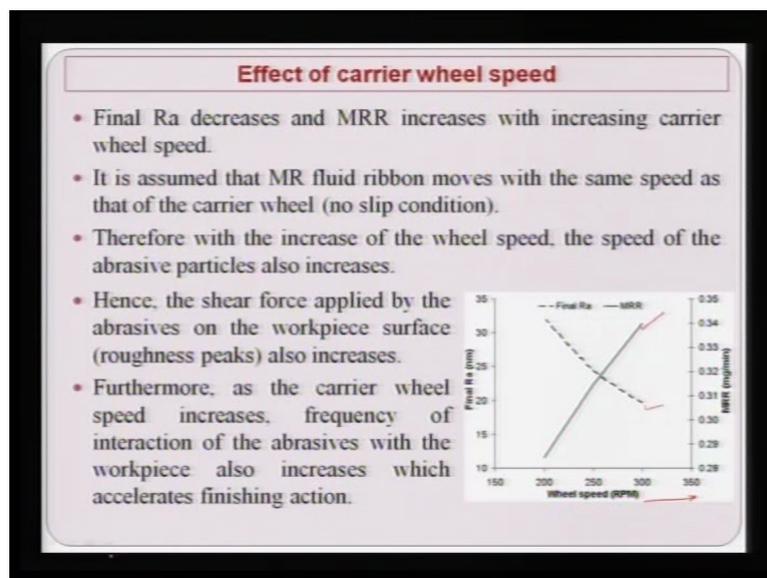
And if surfaces speed of the outer periphery of the wheel is increasing then whatever abrasive particles is there here, suppose this is the abrasive particle, then its speed with respect to the workpiece will also increase.

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That is here is the workpiece will also increase and that means it is very similar to higher cutting speed in conventional metal cutting and that is why you have higher material removal rate. Furthermore as the carrier wheel speed increases, frequency of interaction of the abrasives with the workpiece also increases which accelerates finishing action which is very simple to understand.

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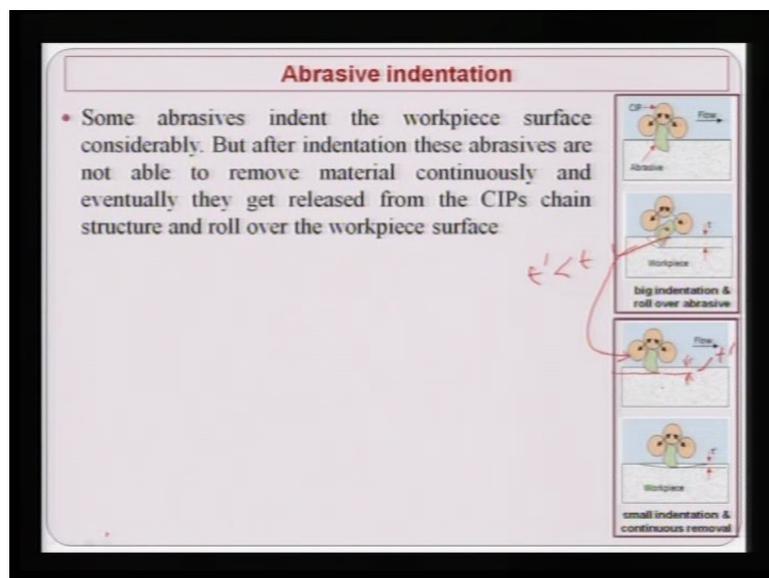


Abrasive indentation, as you can see here some abrasives indent the workpiece surface considerably. But after indentation these abrasives are not able to remove material continuously and eventually they get released from the CIPs chain structure and roll over the workpiece surface. Very nicely depicted over here because as I have mentioned earlier that if normal force is too high then the abrasive particle penetrate inside the workpiece surface quite deep.

And this has to remove the material, then tangential force also should be large enough to remove the whole amount of the material. But if it is smaller then what will happen that chain structure will break and the abrasive particle as you can see in the second figure itself will rotate such that the depth of penetration decreases and (bet) lower depth of penetration it will be able to remove the material from the workpiece.

As you can see here if you come from here to here, the depth of penetration has decreased compared to this particular case as t . This becomes the depth of penetration as t_{dash} and this t_{dash} is smaller than the t .

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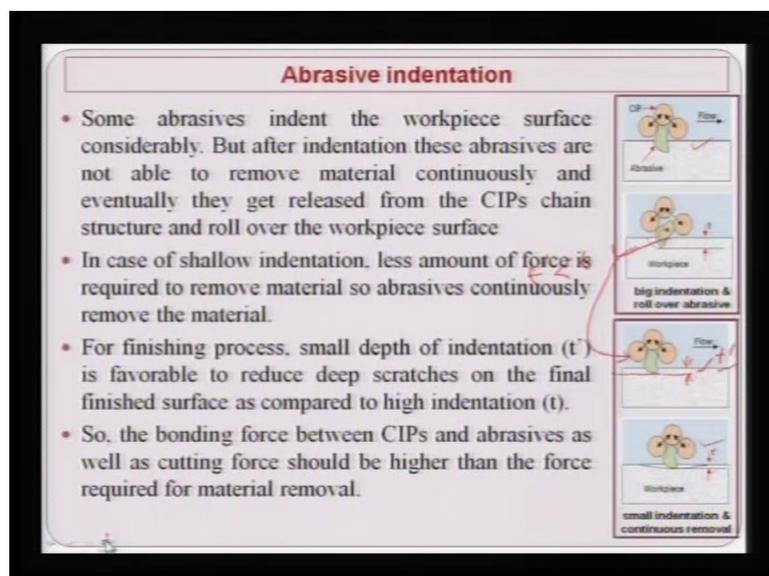


Now since t_{dash} has depth of penetration has decreased so the total tangential force required to remove the material in the form of the microchip will be reduced. And once this is equal to the force being applied by the fluid on the abrasive particle or the force applied by the fluid on the abrasive particle become greater than the resistance of the workpiece material to remove the thickness as t_{dash} , then only it will start finishing.

As you can see here in the last figure this is able to remove the smaller depth of the workpiece material. In case of shallow indentation, less amount of force is required to remove material so abrasives continuously remove the material as you can see in the last figure on the right hand side. For finishing process small depth of indentation is favorable to reduce or to avoid deep scratches on the final finished surface as compared to high depth of indentation as shown figure 1 on the right hand side.

So it is always desirable to have smaller depth of indentation that simply means smaller force compared to the larger normal force. So the bonding force between CIPs and abrasives as well as cutting force should be higher than the force required for material removal.

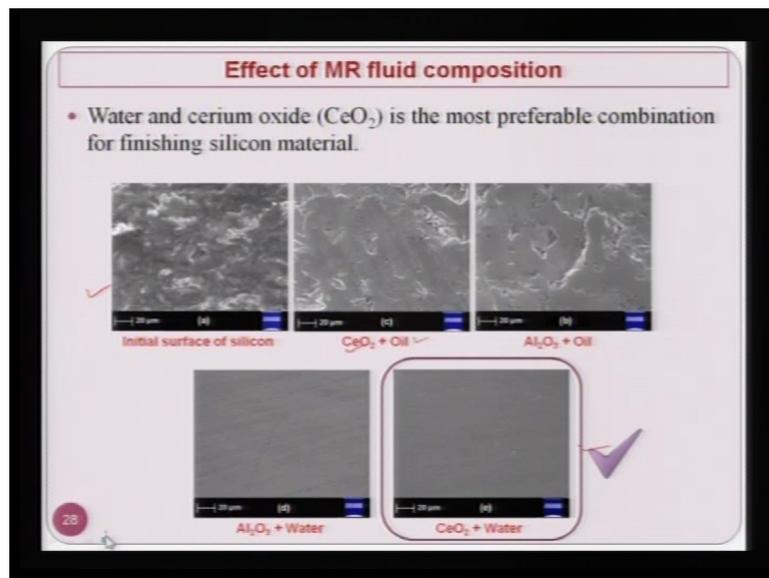
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Effect of MR fluid composition. Water and cerium oxide is the most preferable combination for finishing silicon material. Now here you can see this is the initial surface of the silicon and this is the surface after finishing for certain period of time with the oil as the carrier fluid and cerium oxide as the soft abrasive particles. Then finishing was done with alumina as the abrasive particle and oil as the carrier fluid and you can see the improvement in the surface finish.

Later on water was taken as the carrier fluid and alumina was taken as the abrasive particle and there is a significant difference between the top three surfaces and this particular surface. And finally the surface was finished with water as the carrier fluid and cerium oxide as the abrasive particle. And you can see excellent surface finish obtained on the last case as compared to the last what one case.

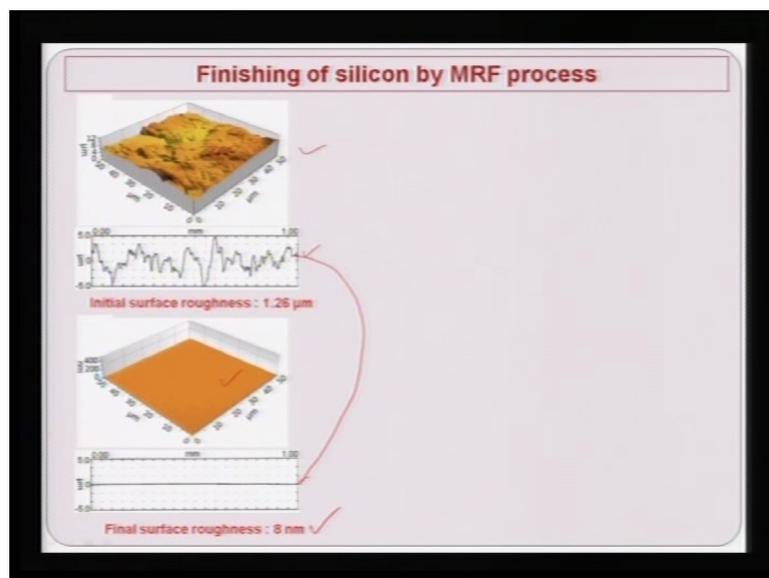
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Now let us see some of the applications of the magnetorheological finishing process. You can see this is a surface which was obtained initially. Silicon single crystal and you can see the surface finish was of 1 point 26 micron and you can see the peaks and valleys in the top surface. Then this was finished by MRF process developed here and you can see the final surface finish achieved is the 8 nanometer and you can see the difference between the surf analyzer plots over here and here.

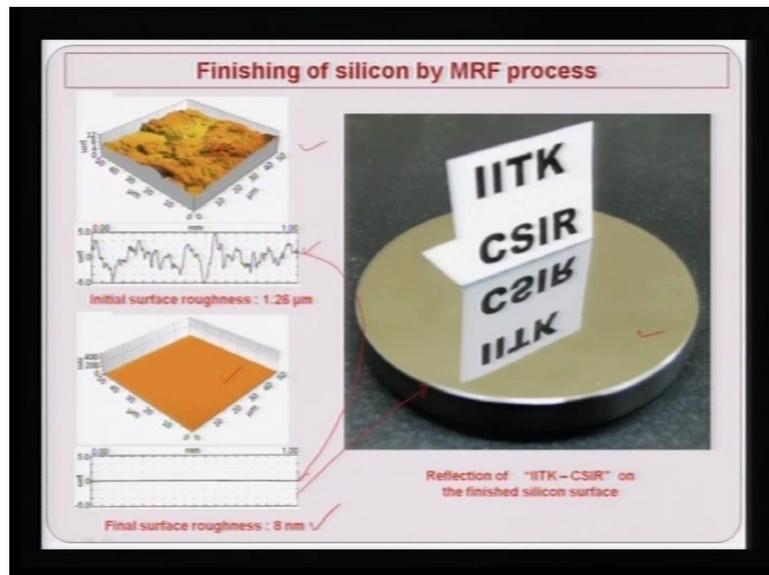
This clearly indicates very good surface finish after MRF process. And this can be clearly seen by AFM plots also over here as well as here.

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Now just to demonstrate it, this is the finished surface that was obtained over here with 8 nanometer surface finish and we (ra) wrote on a piece of paper IITK CSIR and you can clearly see the reflection of these letters on the finished silicon surface.

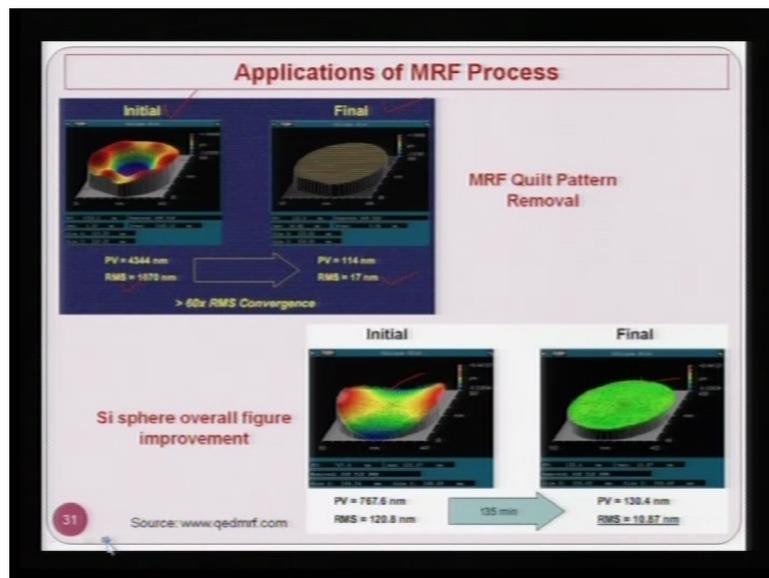
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Now here MRF quilt pattern removal. You can see the one initial surface before finishing and the difference between this surface and the finished surface. Flatness is clearly visible and you can see the difference between the two surfaces. Now RMS values are also very different here 1070 nanometer RMS value while in the finished surface it is only 17 nanometer. Now another film, silicon sphere overall figure improvement can be clearly seen over here.

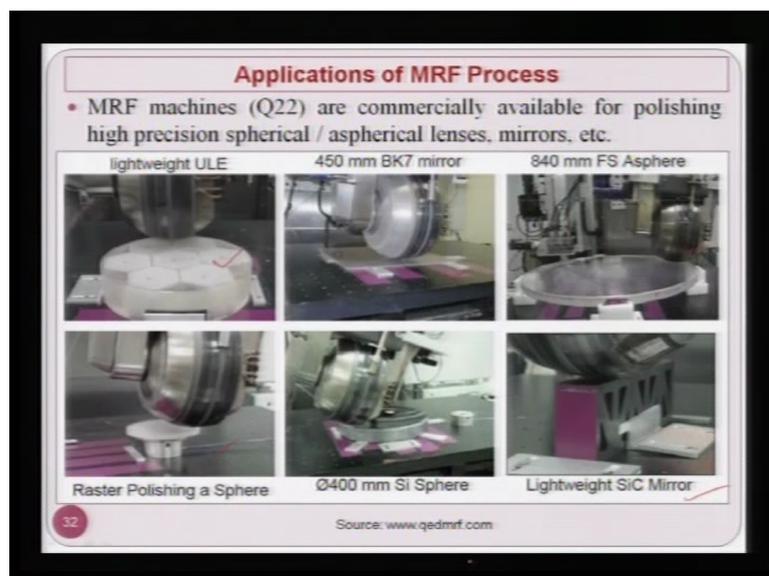
You can see the difference, this is the initial surface and this is the final surface. So the flatness is very clearly visible and RMS value from 120 point 8 nanometer, it has come down to 10 point 87 nanometer in 135 minutes that is around approximately 2 hours. And this has been taken from this particular source.

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Now various many applications are shown here. MRF machines Q22 are commercially available for polishing high precision spherical, aspherical lenses, mirrors, etc. You can see here the way these surfaces are being finished in different cases. This is the lightweight ULE, 450 millimeter BK7 mirror, 840 millimeter AF asphere, then Raster polishing a sphere over here and this is silicon sphere being polished and lightweight silicon carbide mirror is being polished.

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Thank you very much. I am going to show a video about the magnetorheological finishing process setup. Mr. Ajay Sidhpara, PhD scholar in mechanical engineering department, IIT Kanpur will demonstrate the different parts of MRF process, different constituents of the MR

polishing fluids, its working and then some of its applications. So now let us go to the video film. Thank you very much.

Hello everybody, my name is Ajay Sidhpara. I am a PhD student in mechanical engineering department IIT Kanpur. Today I am giving you a brief introduction of magnetorheological finishing process and shortly called as MRF process. The basic component of MRF process is magnetorheological fluid and presently I am giving you preparation of magnetorheological fluid, how it is prepared here? Abrasive particles are required to increase material removal, in other words to reduce finishing time. In the present case the abrasive is aluminum oxide.

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Carbonyl iron particles, in other word magnetic particles are required to make (())(55:39) under the effect of magnetic field. When where the magnetic field is applied, iron particles are aligned along the line of magnetic field and they create a dense structure.

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Water is required as liquid medium so that magnetic particles as well as abrasive particles dispersed uniformly.

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Some additives are also required in the MR fluid so that magnetic particles as well as abrasive particles remain suspended in the MR fluid and to reduce the sedimentation problem. In the present case it is glycerol.

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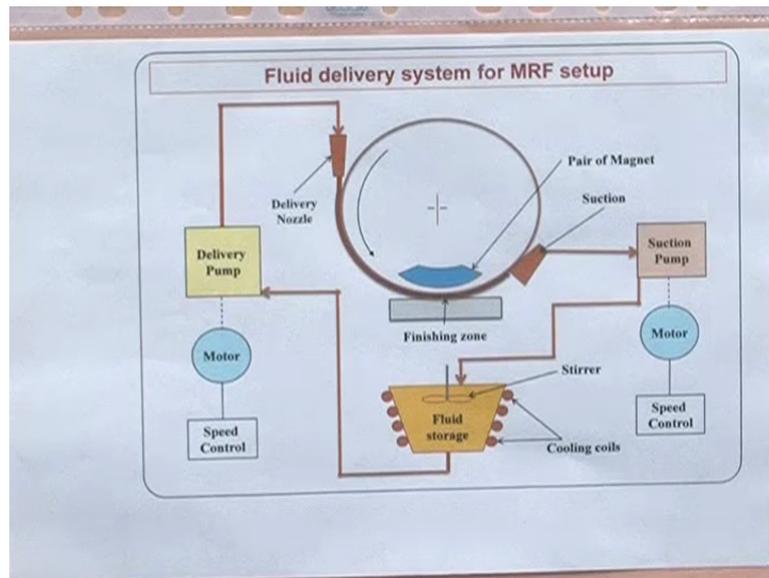


This is the diagram of MRF process which is developed at University of Rochester, U.S.A and later on it is commercialized by QD Technology, U.S.A. This is a carrier wheel on which MR fluid is supplied by the delivery nozzle. Here the workpiece is fixed. When the magnetic field is applied either by permanent magnet or electromagnet, the MR fluid gets stiffened due to presence of magnetic particles.

When the stiffened MR fluid comes in the contact with the workpiece surface it creates a finishing zone which is given here where the material removal takes place due to interaction between stiffened MR fluid and the workpiece. After that the MR fluid is collected from the carrier wheel by this suction pump. From there the fluid is collected to the mixing chamber. It is also called collector from where in the mixing chamber MR fluid is mixed continuously by the stirrer so that particle gets mixed there homogeneously.

A temperature control is also provided to maintain a constant temperature and additional provision of the water supplies is also added so that the loss of water due to (())(57:29) can also be compensated. From the storage, fluid is again circulated at the delivery pump and it is supplied to the carrier wheel by this delivery nozzle.

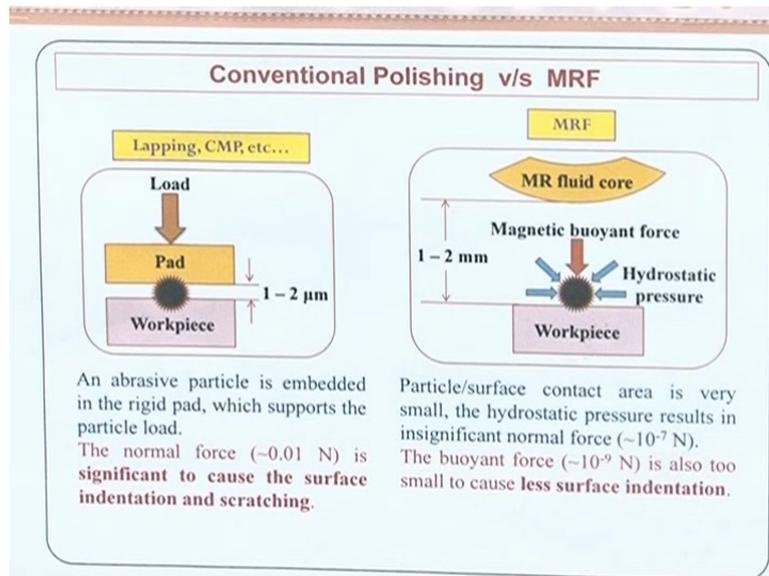
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This diagram shows the forces acting in conventional polishing versus MRF. In conventional polishing such as lapping or chemo mechanical polishing, shortly it is called CMP process, in which abrasive particle is embedded in the rigid pad which supports the particle load. Therefore the normal load around 0 point 01 Newton is significant to cause surface indentation or scratching in case of Nano finishing.

While in the other case in MRF process the particle surface contacts area is very small so that the hydrodynamic pressure results in significant normal force around 10^{-7} Newton. Furthermore the buoyant force is it is also around 10^{-9} Newton. It is also too small to cause surface indentation in case of MRF process. So from this comparative view you can say that the MRF process is far better than this conventional polishing process in case of Nano finishing of different components.

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All the constituents such as magnetic particles, abrasive particle, water and glycerol are mixed together in a proper concentration. After adding all these constituents it is stirred for at least 1 hour to get it mixed homogeneously.

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Now you can see all the constituents of fluid are homogeneously mixed. Now this fluid is ready to use in MRF process. The whole setup is connected to the Z axis of this CNC milling machine so that the working gap can be adjusted by the computer control.

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You can control X, Y and Z movement simultaneously by giving the motion.

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This is a permanent magnet which is covered by (01:00:07) and this all assembly is called as carrier wheel. The carrier wheel is connected to the AC motor through this timing chain. And this AC motor is again connected to the variable frequency drive so that the wheel speed can be controlled automatically by this variable frequency drive.

Even you can give a particular value of the wheel speed so that it can rotate at that particular value only. And this is also required that most of the components should be nonmagnetic so that the magnetic field of line should not be distracted by these components.

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This is a workpiece and this is the workpiece fixture. In the present case this workpiece is single crystal silicon which is to be finished up to nanometer level by this magnetorheological finishing process.

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Now MR fluid is applied on the carrier wheel. Now you can see the MR particles or magnetic particles are aligned from the north pole to south pole around the magnet. You can clearly see the chain structure of the MR fluid particles.

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After that a particular gap is set between the workpiece and the carrier wheel by changing Z axis position. Once the gap is fixed rotation to the carrier wheel is given and X and Y (()) (01:02:15) can also be given to the carrier wheel so that the whole workpiece surface can be covered.

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Here you can see the stiffened MR fluid is interacting with the workpiece surface. At the finishing zone here two type of forces are exerted on the workpiece surface. One is tangential force in this direction.

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It is applied by the rotation of the carrier wheel and another one is the normal force in this direction. It is due to flow of stiffened MR fluid between the converging gap because gap is little smaller than the thickness of the ribbon which is applied on the wheel. And hydrodynamic reaction of the MR fluid also create some normal force.

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This process is continued till the desired surface finish is achieved. Now I will show you the finished as well as unfinished silicon workpiece surface. You can easily see the difference between unfinished and finished silicon surface. This is unfinished silicon surface. You can see there is no any type of reflection is visible on the surface of the unfinished silicon surface.

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Now this is finished silicon surface and you can easily see the reflection of IITK and CSIR on the finished surface of the silicon surface.

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The present result shows that the MRF process is very efficient process for finishing optical as well as hard material. Thank you for your attention.