Advanced machining processes

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Lecture 32
Magnetorheological Abrasive Flow Finishing (MRAFF) Process

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Welcome to the course on advanced machining processes. Today I am going to discuss a nano finishing technique that is named as when magneto rheological abrasive flow finishing process that is the MRAFF process. Here Mr. Manas Das has contributed for this particular presentation.

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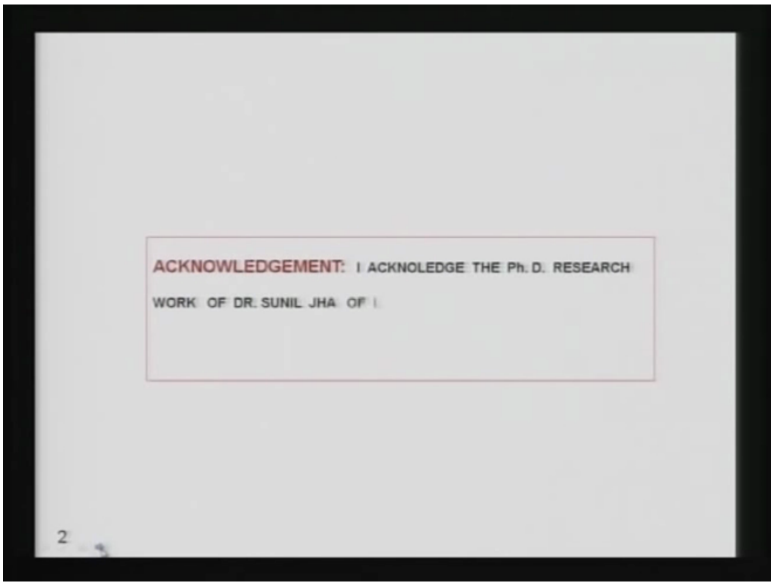

I acknowledged the Ph.D. research work of Doctor Sunil Jha of IIT Delhi and Mr. Manas Das of IIT Kanpur whose work has been quoted in this presentation.

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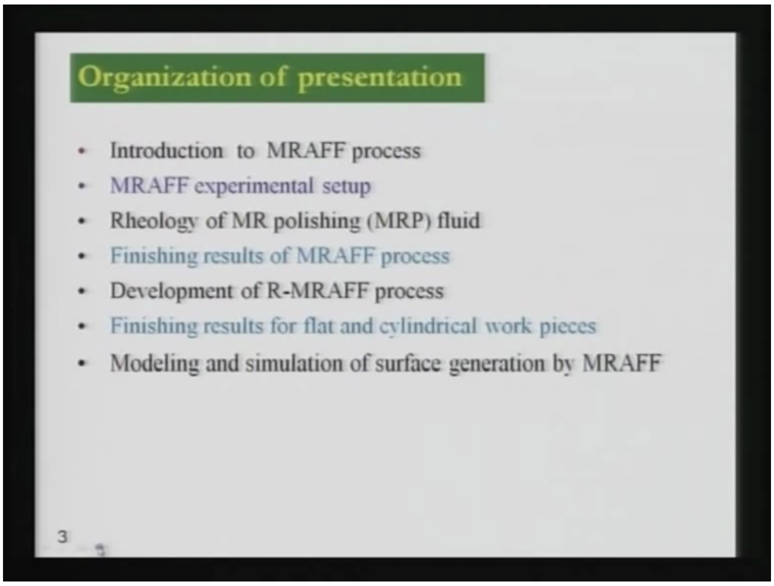

Organization of the talk is introduction to MRAFF, MRAFF experimental setup, rheology of MR polishing fluid. Finishing results of MRAFF process, development of R- MRAFF process and finishing results of flat and cylindrical work pieces and then modeling and simulation of surface generation by MRAFF process.

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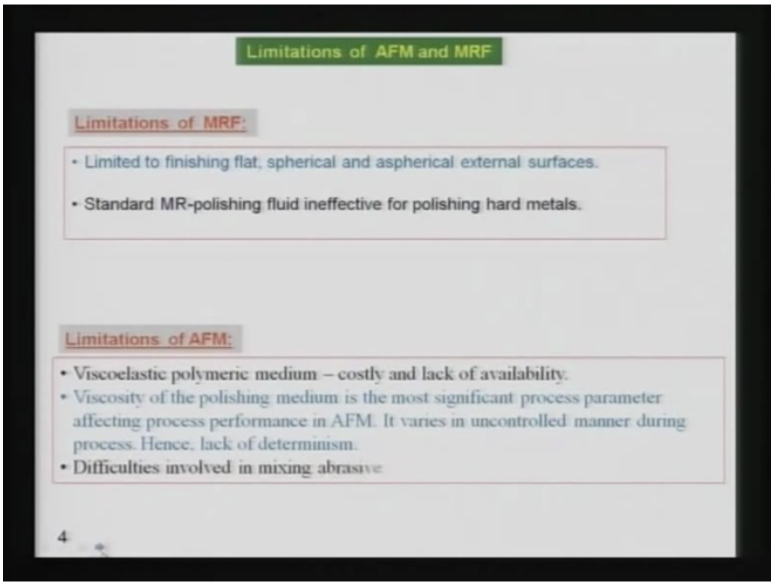

Now we have seen in other lectures the abrasive flow finishing process or abrasive flow machining process and magneto rheological finishing process. We have also discussed the limitations of magneto rheological finishing process it includes limited to finishing flat, spherical and aspherical external surfaces. So there is a shape limitation with MRF process and standard MR polishing fluids are ineffective for polishing hard materials. So this is the material constraint in case of MRF process.

Now recall, let us recall limitations of abrasive flow machining process, it includes viscoelastic polymeric medium which is costly and lack of availability of the medium in India then viscosity of the polishing medium in case of AFM process it is the most significant process parameter affecting AFM process performance. It varies in uncontrolled manner during the process there is no online control of the rheological properties of the medium in AFM process. Hence there is a lack of determinism in case of AFM process.

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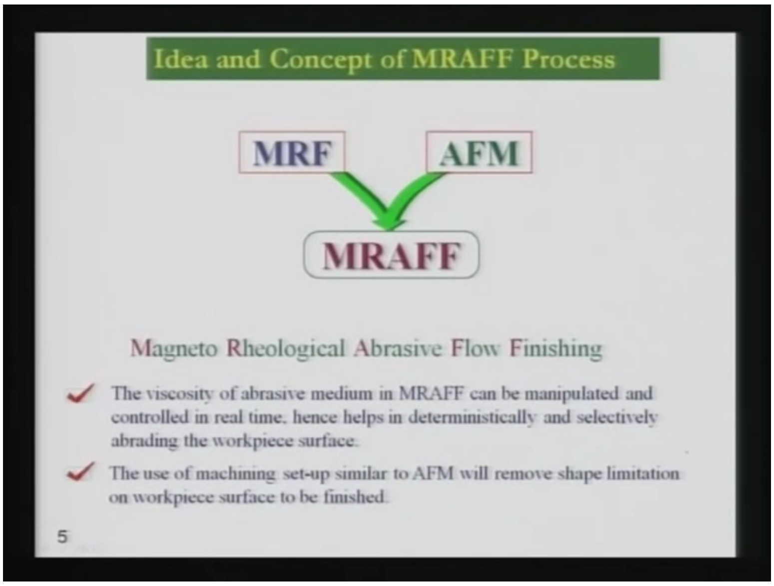

Keeping these limitations in view a new process had been developed and that process will be discussed in the following slides. So MRAFF process magneto rheological abrasive flow finishing process is a combination of magneto rheological finishing and abrasive flow machining process. The viscosity of abrasive medium in MRAFF process can be manipulated and controlled in real-time, hence it helps in deterministically and selectively abrading the work surface. This is very important property of the medium in case of MRAFF process which has been taken from MRF process.

Then the use of machining setup similar to abrasive flow machining setup will remove shape limitations on work piece surface to be finished and this feature is taken from the abrasive flow machining process. So combining these 2 processes or hybridising this 2 processes we have a new process named as MRAFF process.

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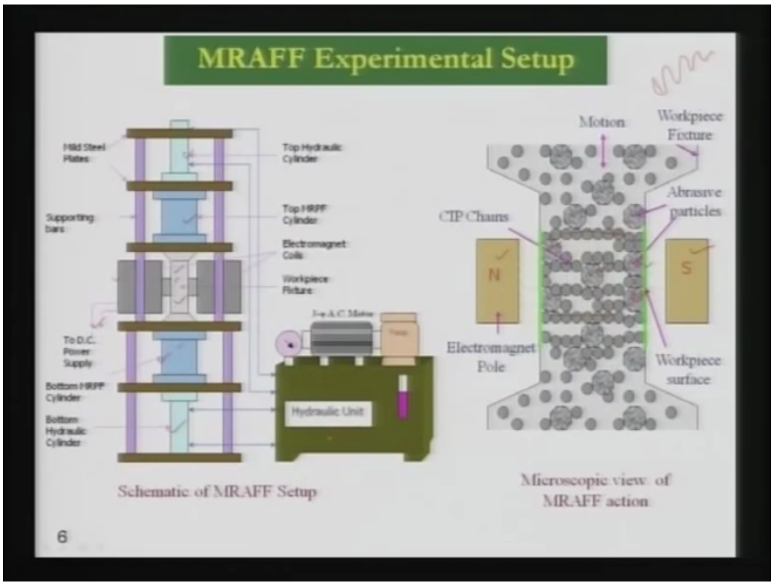

This is the schematic diagram of MRAFF process I will quickly explain this, details will be discussed by Mr. Manas Das in the video film. Now here you can see there is a top hydraulic cylinder, top MRF medium cylinder and here is a work piece which is to be finished and then you have the connection to the power supply because this is the electromagnet over here which is going to give a different magnetic field depending upon the current flowing and the coils of this electromagnet and here is the work piece fixture that is shown there.

And then you have the bottom magneto rheological polishing fluid cylinder over here and this is the bottom hydraulic cylinder.

Now what happens really here that you fill the medium either in the top cylinder or in the bottom cylinder, mostly in the bottom cylinder and then you place the work piece between the top medium cylinder and water medium cylinder with the help of the tooling as shown over there and once these 2 sections are connected and electromagnet is placed in place then hydraulic unit that pushes the piston inside the medium cylinder upward.

So that whatever medium is filled in the bottom medium cylinder that will be pushed upward and it will pass through work piece and work piece tooling and come in the upper cylinder and by the time this medium piston reaches to the top position and then the direction of the flow of the hydraulic oil will change and the medium from the top cylinder will start moving in the bottom cylinder. So up and down motion of the medium takes place through the work piece and when this work piece comes in contact with the medium then abrasive particles start abrading.

As you can see here on the right-hand side these are the abrasive particles and these are the chains which have been formed by the Carbonyl iron particles or iron particles and here is the North Pole and South Pole. So what happens when you bring this medium as I will discuss later on its constituent then these iron particles are Carbonyl iron particles arrange themselves along the magnetic lines of force and they form the change and in between the chains or within the chains abrasive particles which are shown here of the much bigger size in real life they are not show they are of the same size as the iron particles are Carbonyl iron particles.

And when these up-and-down movement takes place of this medium due to the hydraulic cylinder then as you can see here these abrasive particles they rub the work piece surface as shown over here and the peaks of the work piece surface they are like this they are sheared off, as a result the surface roughness value of the work piece surface goes down and this up and down motion does shearing continuously of these peaks on the work surface and with this particular process you can get around 50 nanometre surface roughness value.

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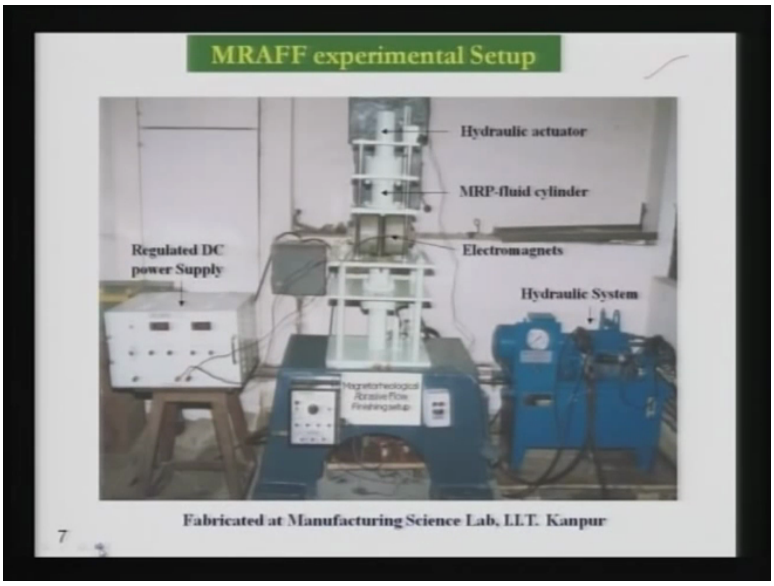

Now hydraulic unit is shown over here. This is experimental setup that has been designed and fabricated at IIT Kanpur manufacturing science lab. You can see some of the things visible over here this is the hydraulic actuator moves the piston in the MRP fluid up-and-down and then here is the electro magnet and between these 2 poles or electro magnet coils there is the work piece which you cannot see very clearly but I am showing it by arrow and then this is the water medium cylinder and here is the bottom hydraulic cylinder and this is the hydraulic unit and this is the regulated DC power supply which is used for this and here you can see the panel for the board where through which you can control various parameters of the system.

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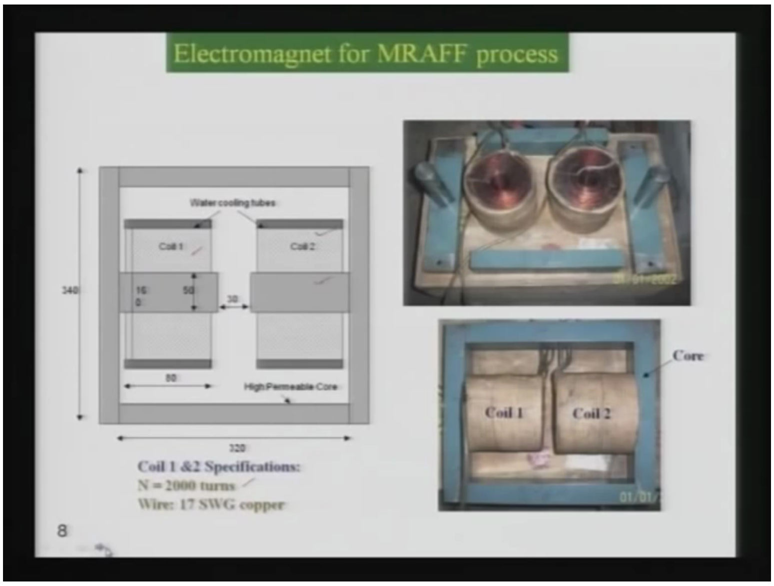

Electromagnet which creates a magnetic field surrounding the work piece surface. In this particular process you can see there are the 2 coils, coil 1 and coil 2 and here are the magnetic materials which generates North Pole and South Pole and in between this North Pole and South Pole there is a gap of 30 millimeters and other dimensions are shown over there, the specifications of these coils are 2000 turns and wire is of 17 gauge. You can see the pictorial view of the same thing, here are the electromagnets coils are there and you can see another view of the electromagnet.

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Here is the work piece fixture, you keep the work piece this fixture is used for keeping the flat work pieces and they can be kept in these 2, to work pieces can be placed at one time, you can have more than 2 slots then you can have more than 2 work pieces being finished at the same time, these are the shapes of the work piece and this is the pictorial view of this particular fixture and you can see this work piece gets fit over here, this is the one and this is for the second one.

And in some cases we use another work pieces, another shape and size of the work pieces like this and there are the different types of the fixtures because size of these 2 work pieces are different, so fixture wise separate one as you can see over there. Now this is the tooling which is connecting the work piece with the medium cylinders. Now you can see the pictorial view of the tooling.

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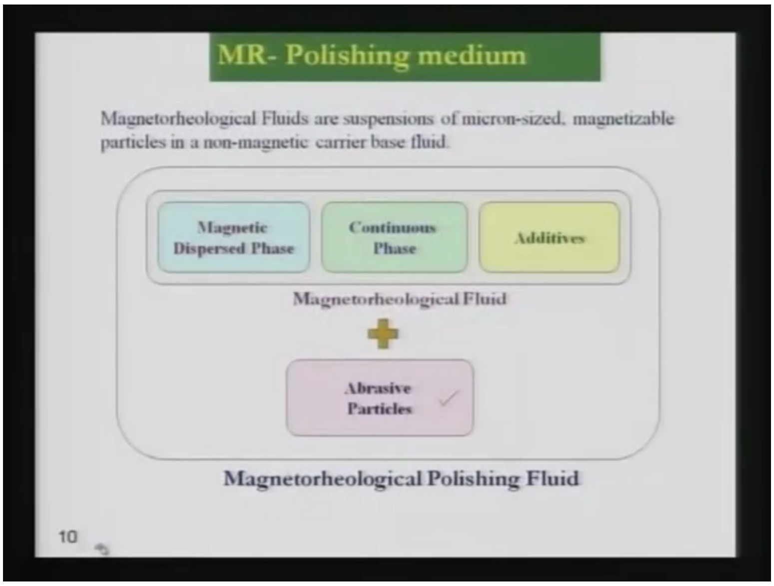

MR polishing medium, this is one of the main components or elements of the whole system and magneto rheological fluids are suspension of micron sized magnetisable particles in non-magnetic carrier-based fluid. Now this MR polishing medium consists following elements one is the magnetic dispersed phase which is nothing but either iron particles or Carbonyl iron particles then continuous paste that normally consist of y and then additives like grease is added as the additive to increase the density of the holes based medium and then abrasive particles are added through this particular medium.

So that the finishing can be done because Carbonyl iron particles are used for forming the chain like structure which holds the abrasive particles and abrasive particles are harder than the work piece material as they are abrading or finishing the work piece surface.

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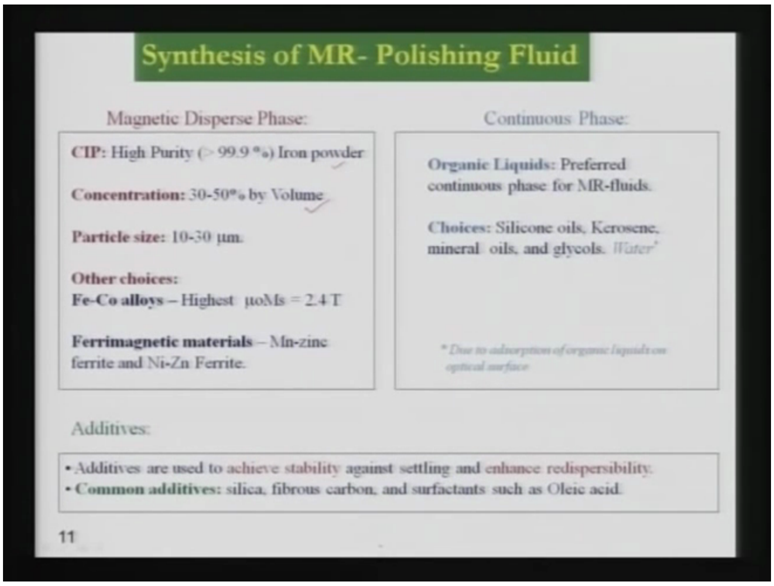

The synthesis of the MR polishing fluid is like this, magnetic disperse phase that is a Carbonyl iron particles they are high purity greater than 99.9 percent pure iron powder and concentration normally taken is around 30 percent but upper limit of this can be as high as 50 percent which is rare particle size varies 10 to 30 micron size and other choices are in place of Carbonyl iron particles they are very expensive then you can use iron cobalt alloy and other one is ferromagnetic materials like manganese zinc, ferrite and nickel zinc ferrite these are the different alternatives.

So you have to choose the one depending upon the cost as well as the magnetic properties then there is the continuous phase this continuous phase consist of organic liquids preferred continuous phase for MR fluids are Silicon oil, kerosene, mineral oil, glycols or water. Due to absorption of organic liquids on optical surface. Additives that are used includes additives are used to achieve stability against settling and enhanced re-dispersibility these 2 are very important properties actually that when you are adding iron particles or Carbonyl iron particles which are much heavier than the density of the based medium that is the mineral oil and grease.

So what happens when you add them then they try to settle down at the bottom and we do not want settling down or sedimentation of these high-density iron particle otherwise finishing will not take this. So for minimising this settling down and you know postponing the settling down we use the additives for that particular purpose and common additives are silica, fibrous carbon and surfactants such as Oleic acid.

Now abrasive particles also have density higher than the density of the base medium or liquid and they are settling down of abrasive particle is also not desirable. So these additives help in minimising the settling down of abrasive particles as well as Carbonyl iron particles or iron particle.

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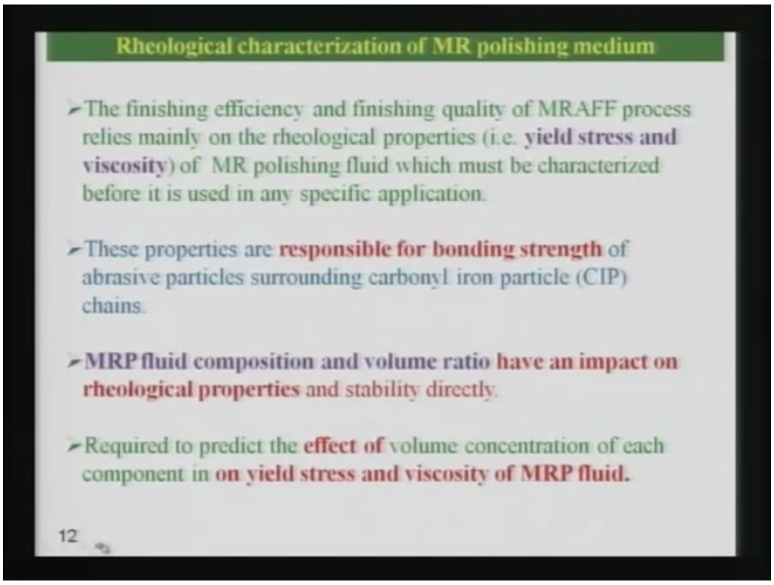

Rheological characterization of MR polishing medium, the finishing efficiency and this equality of MRAFF process relies mainly on the rheological properties which are yield stress and viscosity of MR polishing fluid which must be characterized before it is used in any specific application because the performance of any medium will even upon what is its yield strength and what is its viscosity on line?

And it is desirable that both of these do not change during the process in an uncontrolled fashion but we do not have any control on these properties in case of AFM process abrasive flow machining process but we have control in case of magneto rheological finishing process and that property has been taken in MRAFF process. So you can control these yield stress and viscosity externally by changing the magnetic field with the help of the current supply to the electromagnet.

These properties are responsible for bonding strength of abrasive particles surrounding the Carbonyl iron particle chains, as I showed you in the earlier slide that Carbonyl Iron particles forms the chain and these abrasive particles are either within the chain or between the chain and the strength of these chains depends upon the magnetic field being applied over there.

MRP fluid composition and volume ratio have an impact on rheological properties and stability directly.

What is the percentage of the Carbonyl iron particles in the medium and what is the percentage of the abrasive particles in the medium? Both of them have a significant effect on the rheological properties of the MR polishing fluid and the rheological property of the fluid effect the performance of the MRAFF process. Required to predict the effect of volume concentration of each component in yield stress and viscosity of MRP fluid. Lot of study has gone into it about the effect of the percentage of Carbonyl iron particle and percentage of abrasive particles on the yield stress of the medium and viscosity of the medium.

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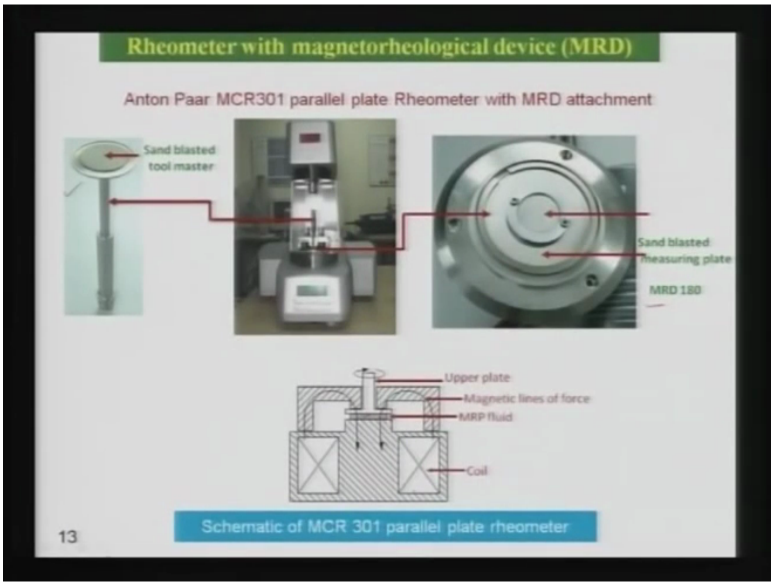

Rheometer with magnetorheological device, now this is the rheometer which has been used for characterizing the MR polishing fluid and this is Anton paar MCR 301 parallel plate rheometer with MRD attachment. You can see sandblasted tool master is there and then sandblasted measuring plate is over there. Now speciality of this plate is that this is sandblasted, so that you know the effect of abrasive particles on the plate is minimum because the real-life medium is consisting abrasive particles as well as iron particles when you are evaluating their properties that these particles are mixed in the medium and you are using them on this particular rheometer. So it may damage the normal plate of the rheometer, so special-purpose plates that is sandblasted plates are used for this evaluation of the properties of the MR polishing fluid.

Now how it works you can see here, this is the coil over there here is the plate, upper plate is there and then coil is there because we are evaluating the properties of the MR polishing fluid under the magnetic field because MRAFF is use the magnetic field during finishing, so at different magnetic field strength the fluid characteristics have been evaluated, so you can see calls are there which create the certain magnetic field and here is MR polishing fluid and when this plate rotates shearing action takes place and with the help of the data provided by this rheometer yield stress and the viscosity of a particular composition of the MR polishing fluid are evaluated.

With the help of this rheometer you can find out the properties of the medium at different shear rates, you can also vary the temperature of the medium because during MRAFF process or AFM process or MRF process the temperature of the medium changes as finishing keeps taking on. So we should know the properties or rheological properties of the medium at different pressure also. So you can utilize this particular rheometer for that purpose.

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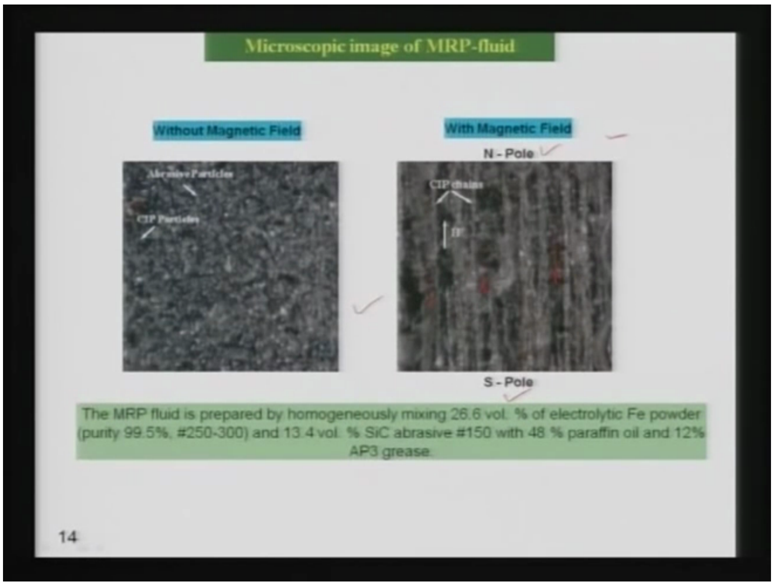

Now this is a very interesting picture you can see here on the left side abrasive particles, iron particles randomly distributed in the medium that is the base liquid which consist of oil as well as glycerol but when you are applying the magnetic field you can see columnar type of structure has been formed, you can clearly see these are the columns or the chains being formed and here is the North Pole and here is the South Pole and this is a specific characteristic, special characteristics which helps in applying the force on the work piece surface and when these abrasive particles in the chains or between the chains come in contact with the work piece then they do the finishing.

Something very similar, close to what you do in case of grinding wheel. Here it is, it works as a flexible grinding wheel, in the normal grinding wheel you have the bonding material which is the fixed one no flexibility is there. So the MRP fluid is prepared by homogeneously mixing 26.6 volume percent of electrolytic iron powder and 13.4 percent silicon Carbide abrasive of 150 mesh size 48 percent paraffin oil and 12 percent AP3 Grease that was used for this particular medium for which picture is shown over here.

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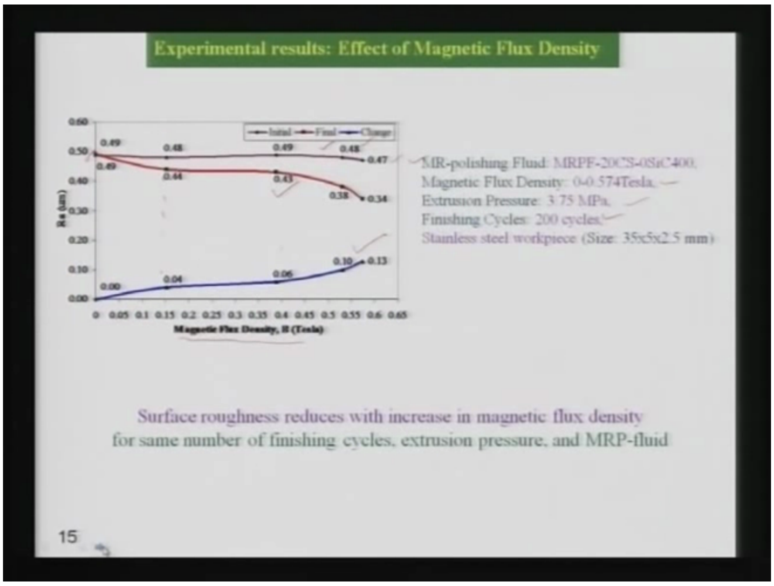

Now when the experiments were conducted using the medium in the MRAFF process you can clearly see very interesting picture over here, this is the initial surface roughness in terms of micron RA value as you can see here for different work pieces 1, 2, 3, 4, 5 work pieces are there then finishing was done and when finishing was done for a certain number of cycles then you can see the surface roughness, this is magnetic flux density and as the flux density is changing here at 0 flux density there is no change in the Ra value of the work piece.

When there is a certain magnetic field applied then you can see there is a change from 0.48 RA to the 0.44 Ra value and if you apply the higher magnetic field for the same number of cycles then it changes from 0.49 to 0.43 micro-meter Ra value and in the last but one case 0.48 to 0.38 and in the last case 0.47 to 0.34. So actually magnetic field is clearly indicating its influence on the finishing rate means per second or per cycle how much change in the Ra value of the work piece surface has taken place and this is indicated by the blue colour line that has magnetic field is increasing the change in the Ra value is increasing continuously.

And these are the details under which these experiments were performed, this is the polishing fluid, magnetic flux density 0.574 Tesla upper limit and then extrusion pressure 3.75 mega-Pascal, finishing cycles fixed 200 and work piece material is stainless steel work piece and the size is 35 by 5 by 2.5 millimetre. Surface roughness reduces with increase in magnetic flux density as you can clearly see for same number of finishing cycles, extrusion pressure and MRP fluid.

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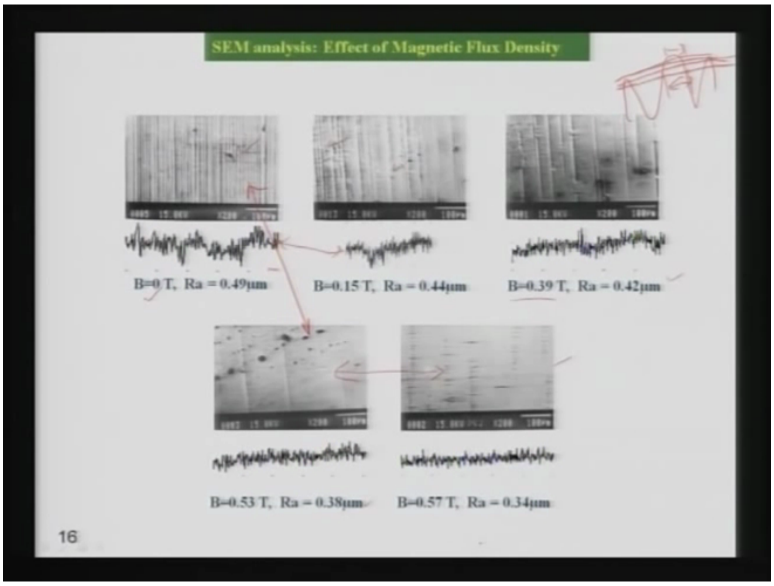

Now then some of the pictures SEM pictures were taken for the work pieces in the beginning before finishing and you can see here this is the work piece which has a 0.49 micro-meter as Ra value and this is after grinding that was obtained with 0 magnetic field and here you can see B is equal to 0.15 and finishing has been done and you can clearly see the difference between the surf analysers plots taken over here as well as in these SEM pictures also you can clearly see that the peaks are sheared off and you know these width of the peaks is increasing because continuously some of the peaks are being sheared off.

So as you go down, as you can see here as you shear off then their width keeps, width will keep increasing which was is this now and earlier it was only this much. So that is what clearly you can see over here. Now if you increase the flux density and you can see B is equal to 0.39 Tesla, Ra value is 0.42 it further goes down and at 0.53 Tesla it comes down to 0.53 you can clearly see the difference in these 2 figures, they have shear large number of peaks and it is becoming more or less the flat surface and then you get 0.34 and you can see the difference in the last 2 figures that means this is the better surface then this left-hand side surface and its Ra value is 0.34 micro-meter. So it clearly indicates the effect of magnetic field on the rate of finishing in case of MRAFF process.

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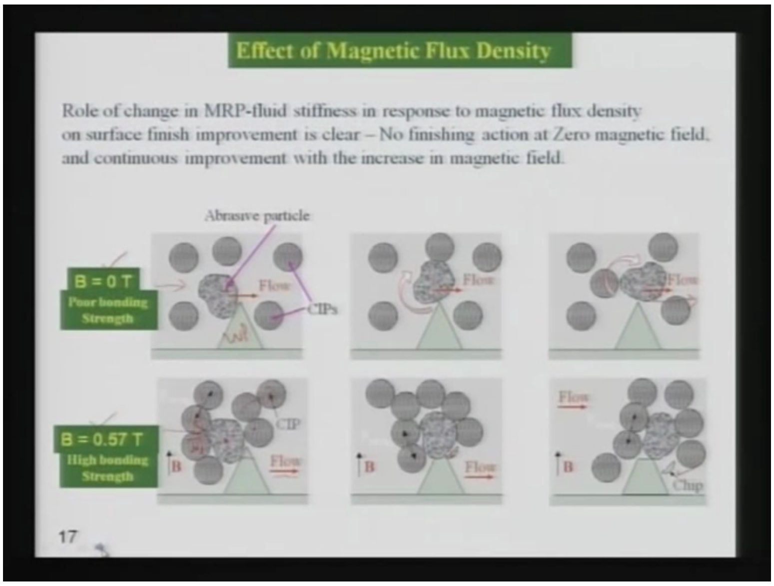

Now how it is working? If you see here what is happening that when there is no magnetic field abrasive particles and (()) (26:25) are randomly distributed and when you are pushing this medium forward this is the abrasive particle it just goes above the peak of the work piece surface this is the work piece surface and without removing any material because there is no strength in the iron particle or there is nothing which holds the abrasive particles and applies the force.

So it just jumps and flows over the peak and comes out without any removal of material but in the second case where magnetic field is say 0.57 Tesla then what is happening you can clearly see the chains are being formed of the iron particles or CIP and they are holding the abrasive particle between the (()) (27:11). Here are the abrasive Carbonyl iron particles or iron particles they are holding the abrasive particles and when you are pushing it in the direction of arrow as flow shown over here that this abrasive particle will shear of the peak of the work piece surface.

It will depend upon what is the strength of the chains formed by the iron particles. So you can see in the second figure it has removed little amount of material from the peak of the work piece surface and this material is nothing but the chip as you can see in the third figure it has been removed and it is called as the microchip or nano-chip depending upon the size of the chip and this is how really the removal of the material takes place in MRAFF process. So it is nothing but mechanism of material removal in case of MRAFF process.

So role of change in MRP fluid stiffness in response to magnetic flux density on surface finish improvement is clear. No finishing action at 0 magnetic field that I have shown here B is equal to 0T Tesla and continuous improvement with the increase in magnetic field that have shown in the earlier slides also.

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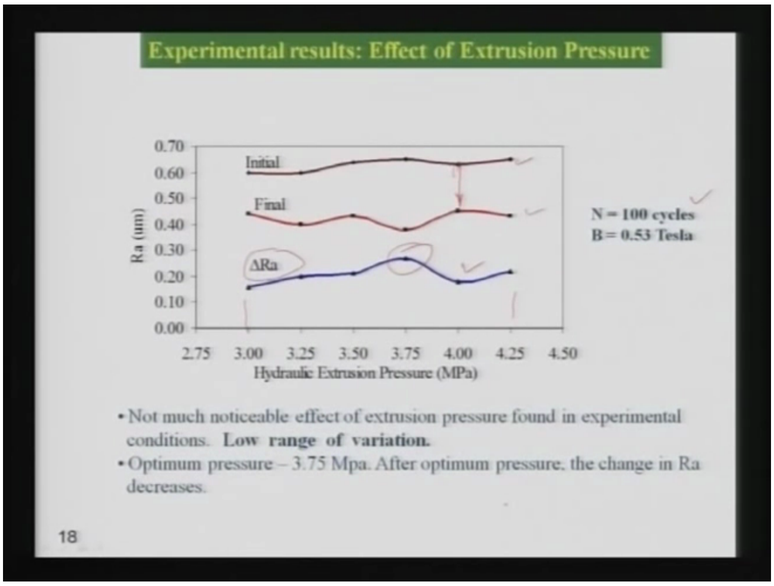

Now here you can see the effect of extrusion pressure on surface roughness value Ra. Now you can see here this is the initial surface roughness and this is a final surface roughness the difference between these 2 is given here by the blue colour line and you can see here clearly that there is not too much or not much effect of hydraulic extrusion pressure on the change in or Ra value or final Ra value that you are achieving and this experiments have been done for 100 cycles at 0.53 Tesla as the magnetic field.

Not much noticeable effect of extrusion pressure is found in experimental conditions low range of, second point you have to note that the variation that has taken place in the Hydraulic extrusion pressure is in definitely in low range that is 1.25 mega-Pascal only but whatever is the range taken during experimentation not much effect on Ra value is obtained that of hydraulic extrusion pressure.

Optimum pressure in this particular case obtained is around 3.75 mega-Pascal as you can see here, here is the maximum change delta Ra there is a maximum change is in Ra value that is why for this range of pressure this is the optimum value or the value which gives maximum delta Ra.

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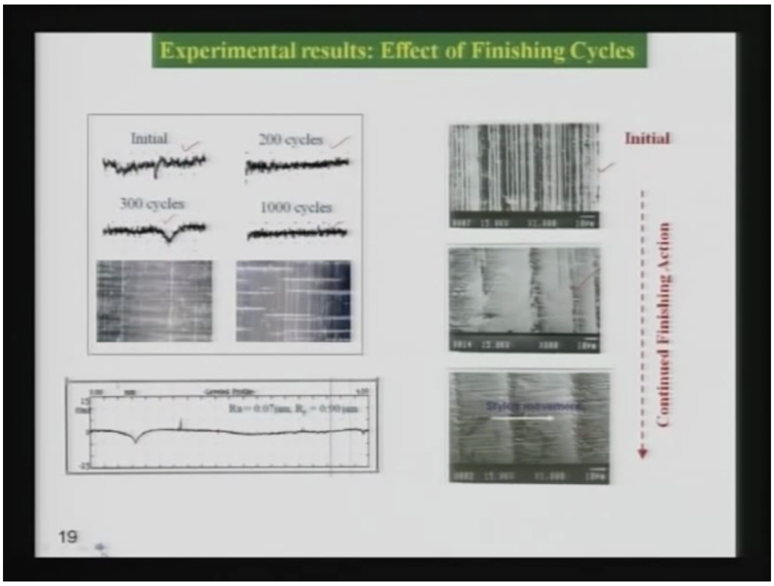

Experimental results effect of finishing cycles you can clearly see here this is for 300 cycles, this is the initial surface, this is after 300 cycles, this is 200 cycle and this is 1000 cycles and we clearly see that as this is the surf analysers plots we see that as the number of cycles is increasing the surface roughness undulations are decreasing continuously. Sure this is what you can see, this is the initial surface and after certain number of cycles you can see the difference between this and this that peaks have been sheared off and the width of the peaks is continuously increasing.

Here it is further increased and sheared off and only at larger intervals you are finding the valleys or the deep valleys and the stylus moment is in this particular direction.

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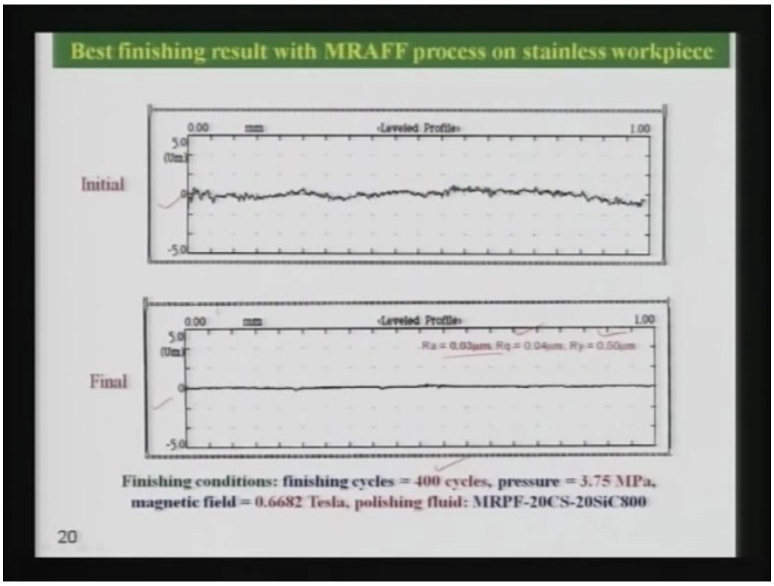

Now you can see the difference in the surf analyser's plots after finishing and before finishing. Here is the initial surface and this is after finishing with MRAFF process and you can see the surface finish that is obtained is about 30 nanometers after finishing and other Rq and Ry values are also given over there. So you can see, you can get as good as 30 nanometers surface finish in case of MRAFF process. Finishing conditions are given over here which you can see and the numbers of cycles used are 400 only.

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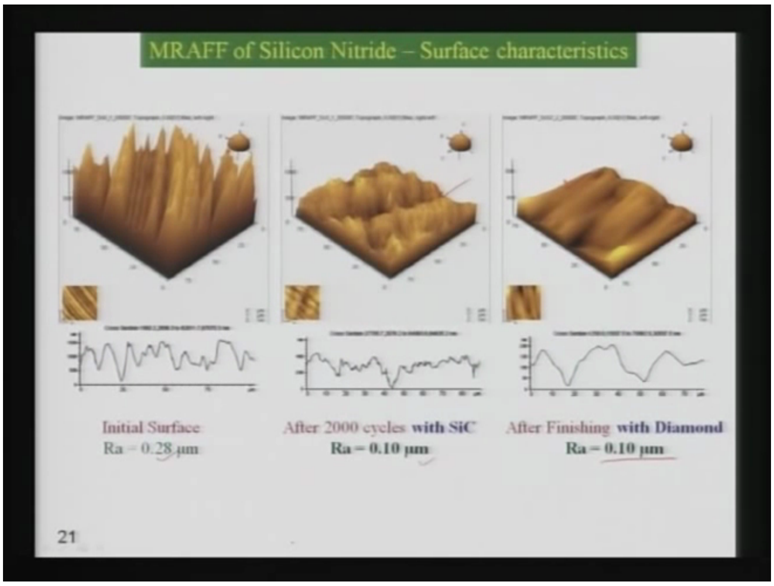

Now these are very interesting pictures, see here this is the initial surface roughness after grinding operation and this is the SEM photograph and you can see what kind of peaks and valleys are there and surface roughness is 0.28 micron Ra value now if you see here after 2000 cycles the finishing has been done with the help of Silicon Carbide abrasive particles, Ra value from 0.28 has come to 0.10 but again you can see the surface quality or surface texture is not that good as it should be.

So what we did? In place of SIC conducted some experiments with the diamond powder having the same properties means same size and same again 2000 cycles and you can clearly see again the surface roughness obtained is about 0.1 micron but there is this difference in the surface quality obtained by diamond and that obtained by Silicon Carbide although diamond particles are very expensive compared to Silicon Carbide but the surface quality improves although surface roughness value may not decrease to a large extent.

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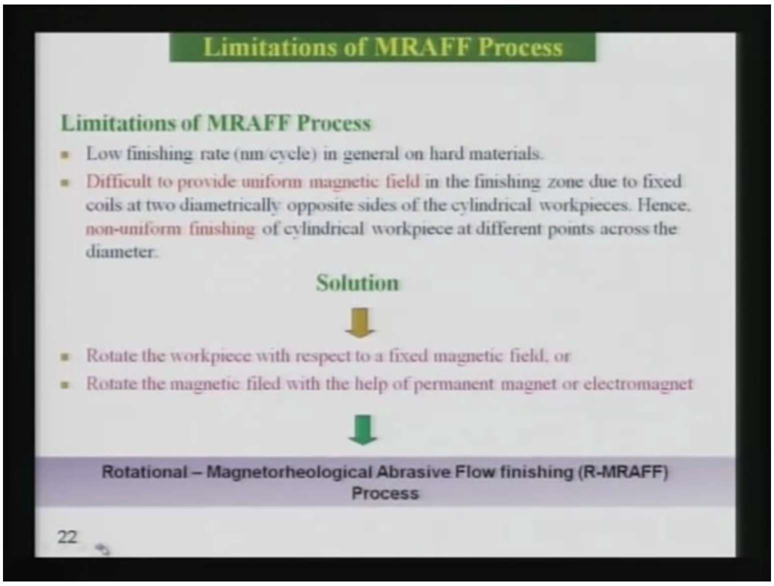

There are certain limitations of this MRAFF process that I have just discussed you and these limitations are important to note that low finishing rate that can be expressed in terms of nanometer per cycle in general on hard materials. Difficult to provide uniform magnetic field in the finishing zone due to fixed coils at 2 diametrically opposite sides of cylindrical work pieces. Hence non-uniform finishing of cylindrical work piece at different points across the diameter will take less which is again not desirable.

So question is what is the solution for this problem to resolve? So we have a solution that rotates the work piece with respect to the fixed magnetic field. So what will happen? When you are rotating then all the surface whole surface of the work piece will get uniformly finished because whole area will pass through the high magnetic field low magnetic field. So high magnetic field will give you a final surface finish which is more or less uniform.

Rotate the magnetic field with the help of permanent magnets or electro magnets. Now another point to note here is that normally people use electromagnet but it is difficult to move or rotate the electro magnet. So in place of electromagnet we had used permanent magnet, so that the magnets can be rotated and if you are rotating the magnet then medium will be rotating with respect to the work piece and if medium is rotating with respect to the work piece it really does not matter whether you rotate the work piece and medium is fixed or you rotate the medium than work piece is fixed because what you need is a relative motion between the abrasive particles and the work piece. So rotational magneto rheological abrasive flow finishing process was developed based on this particle of principle which I am going explained in brief.

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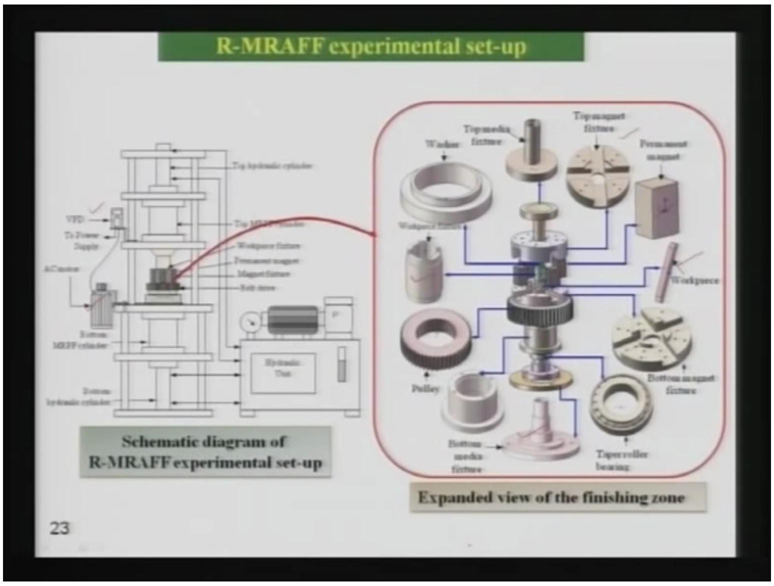

Now system is the same as I have already explained to you except that here you can see this is the belt drive and here are the permanent magnet that have been fixed in the magnetic fixture and this whole device is rotated with the help of the A/C motor and the rpm revolutions per minute of this particular A/C motor can be controlled by VFD variable frequency drive. So what is really doing here is that you are rotating these permanent magnets with the help of the A/C motor in the chain drive.

And once these magnets are rotating then due to the rotation of the magnet, magnetic field is rotating around the work piece surface and when magnetic field is rotating then the medium is also rotating with respect to the work piece surface and this is the expanded view of the setup that has been developed for this particular purpose you can see here these are the permanent magnets, this is the work piece, this is the work piece fixture and you have gears etc and connecting plates and this is the permanent magnet which are shown over here and when you rotate this whole of the setup moves.

And you can see here bottom medium fixture and here is the top magnet holder or fixtures etc are there, so you can have in place of this type of the work piece or you can have the other type of the work piece as I have shown to you in the earlier slide. Configuration of permanent magnets in R- MRAFF process.

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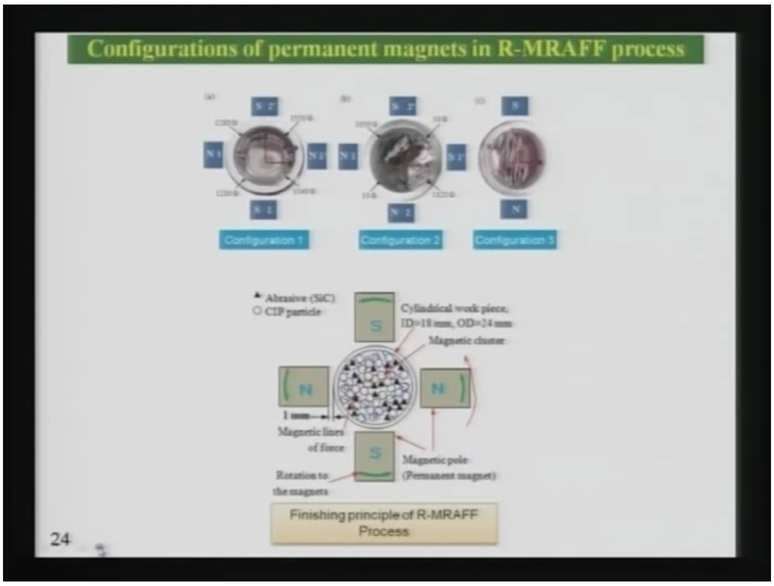

This is an interesting figure, here you can see these are the 3 pictures that we have taken by putting the magnets, permanent magnets in 3 different ways, configuration 1 you can see here North North-South South, in case of configuration 2 you have North-South and south north and in configuration 3 you have only to magnets South and North and you can clearly see in all the 3 pictures that in the first configuration only you have the uniformly distributed medium all along the magnet and the brush be informed is uniformly distributed.

While in second case, second configuration you can see the magnets brush is formed and maybe stronger than what you have in case of one but this is not uniformly distributed there are certain pockets where there is no brush and there are other pockets where a strong brush is being formed. So in the third case we tried with 2 magnets only and again the similar problem was there that there are certain pockets where there are no brush being formed and there are certain areas where strong brush is being formed or continuous you can see the change from one end to another end is being formed which you do not see in other 2 configurations.

So it is strong but not uniform that is why it was decided that configuration 1 is going to give better uniform surface finish as compared configuration 2 and configuration 3. Hence consideration one was adopted. You can see here schematic diagram finishing principle of R-MRAFF process.

Now what is happening in R- MRAFF process compared to MRAFF process? In MRAFF process electromagnets or permanent magnets were fixed. So there was only axial motion of the medium due to the hydraulic upper cylinder or piston and hydraulic bottom piston. Here what is happening that these magnets, 4 magnets are rotated as shown by the arrows over there, green colour arrows and there are magnetic clusters being formed you can clearly see the magnetic particles and the abrasive particles and these clusters are being formed.

And when these magnets are rotating then whole of this medium is also rotating and once the medium is rotating then there is relative motion in rotating direction between the abrasive particle and the work piece surface and do not forget that this medium is continuously moving up and down due to the upper hydraulic cylinder and Lower hydraulic cylinder, so there are 2 motions continuously taking place.

One is the circular motion due to the rotation of the electromagnets and another is the axial motion due to the moment of the piston of upper medium cylinder and piston of lower medium cylinder. As a result of these 2 motions you get the helical motion of the abrasive particles.

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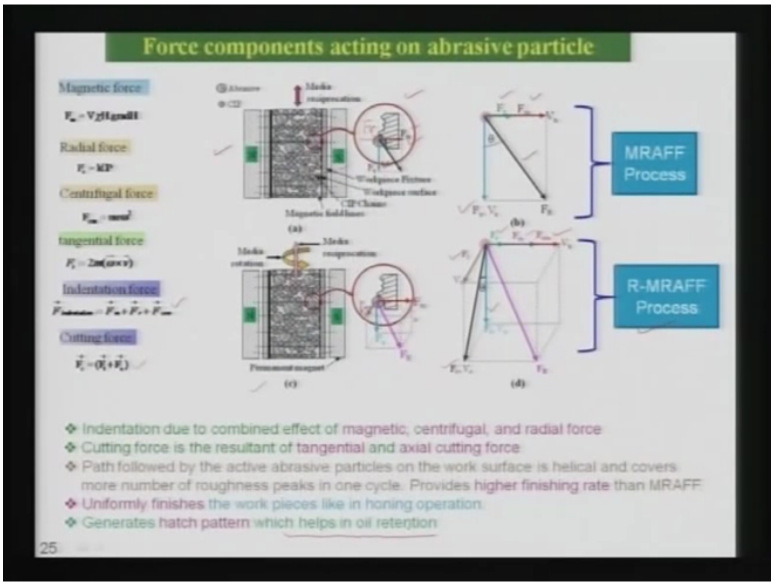

Now the question arises what is the advantage of rotating the magnets, so that you get helical motion of the abrasive particles with respect to the water piece surface. Now that is shown over here with the help of the force diagrams, you can see on the left side you have the electrode North and South poles and here is the figure which shows the mechanism of material removal normal forces is acting and here is the axial force.

Normal force is responsible for the penetration of the abrasive particle in the work piece and axial force is responsible for the removal of the material from the work piece in the form of Micro nano chips. So there are only 2 forces that are acting Fm as well as Fa and material is being removed in the form of microchips and if you see here on the right-hand side figure Fr is the resultant force, Fm is a magnetic force that is acting and Fa is the axial force that is acting but due to the extrusion pressure axial force is there but radial is also acting at the same time, so there are the 2 forces Fm and Fr which are shown here they are responsible for the penetration of the abrasive particle inside the work piece that is this force here Fm is there and here you have Fr also there.

So both these forces are responsible for penetration and axial force is responsible for removal of material in the form of the micro-nano chips but in case of R- MRAFF process if you see here there is a rotation and because of rotation 2 additional forces are acting, one is the centrifugal force another is the coriolis force and you can see here that on the left side here is a again chains are being formed of the iron particles, abrasive particles are there and the rotation is being given to the medium.

Now here within the circle if you see there are various forces which are shown over there. Now if you see on the right-hand side the force, normal force that is responsible for the penetration of the abrasive particle into the work piece is Fr, Fm here it is assumed that magnetic force that is acting is normal to the work piece surface otherwise there will be a normal component of the magnetic force and axial component of the magnetic force and then there is a centrifugal force, although the forces are responsible for the penetration of the abrasive particle into the work piece.

On the other side there is a tangential force because rotary motion is there due to the rotary motion tangential force is acting on the abrasive particle and there is the axial force due to the axial motion of the medium and both these forces (()) (42:58) in the Fc that is the cutting force and this cutting force is responsible for the removal of the material in the form of the micro-nano chips.

So this is how really you are getting that additional forces are acting on the abrasive particles the increase the finishing rate in case of R- MRAFF as compared to the MRAFF process as will see later on in the results. Now these are the equations which can be used for evaluation of the radial force, magnetic force, centrifugal force, tangential force and total force that is responsible for indentation is given here that vectorial sum of Fm, Fr and F centrifugal force and the cutting force that is responsible for removal of the material as you can see here that is the vectorial vector sum of tangential force and axial force as shown over here.

Indentation is due to the combined effect of magnetic a centrifugal and radial force and cutting force is the resultant of tangential and axial force as I have already explained, path followed by the active abrasive particles on the work piece surface is helical, this is important as I have mentioned that helical path is being followed by the abrasive particles and covers more number of roughness peaks in one cycle, why finishing rate is higher?

Because when it is moving in a helical path in one single stroke it will cover more number of the peaks, remove the material from more number of peaks and total area where from material is being removed will be more than in case of R- MRAFF process and that is why you have higher finishing rate in case of R- MRAFF process as compared to MRAFF process. Secondly you get uniformly finished surface of the work piece as compared to the MRAFF process and it is the operation something very similar to the honing process where you have the crosshatch pattern.

In this particular process also you get the crosshatch pattern as I will show you later on with the help of the SEM photograph. It generates crosshatch pattern which helps in oil retention especially in case of bearing etc where oil should be retained in the bearing for minimising or reducing the friction this kind of crosshatch pattern surfaces are more useful rather than other surfaces.

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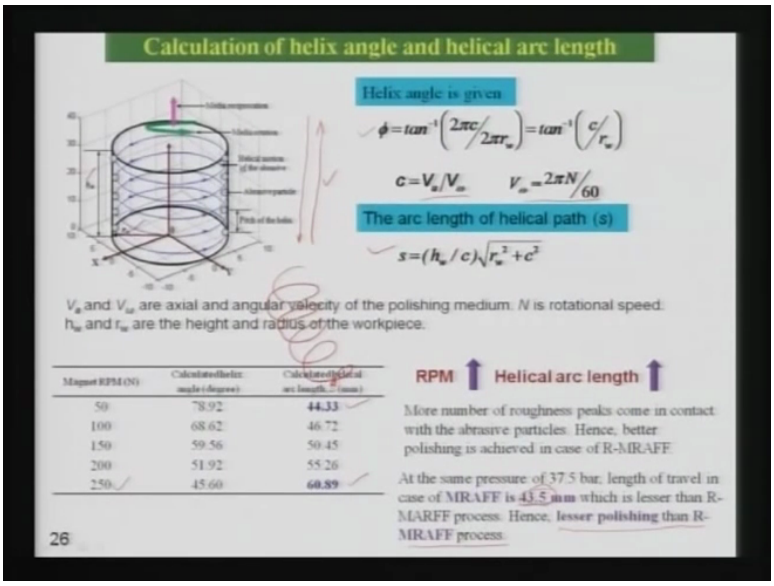

You can calculate the Helix angle with the help of these equations given over here. Now this Helix angle 5 can be calculate it 2pic over 2pirw or tan over c over rw where c is given by Va over V omega and V omega is given by 2piN over 60. The arc length or the length being covered by the abrasive particles R- MRAFF is bigger or larger compared to the case the length being covered by the abrasive particle in MRAFF process.

If you see in MRAFF process the work piece is moving in a straight line up, down or up but in case of R- MRAFF process the work piece is moving in the helical path like this and when it is moving in a helical path like this the total length covered by the abrasive particle, sorry it is the abrasive particle which is rotating in the helical path, so total length covered by an abrasive particle in the helical path is more than it is being covered in the straight-line path as shown over here.

So you can calculate the arc length of helical path s is equal to how over C multiplied by under root of r w square plus C square and Va and V omega are axial and angular velocity of the polishing medium, this medium is rotating due to the rotation of the magnets, N is the rotational speed in revolutions per minute, how and rw are the height and radius of the work piece that you can see over here.

Here is the height hw and this is the radius of the work piece and that is shown over here by rw. Now this gives you an important information that total length of the work piece is here and when you are rotating these magnets by 50 rpm the calculated helical arc length is 44.33 millimeter while you are rotating it by 250 rpm this length increases to 60.89 and which is just approximately double of what you have the axial movement of the medium or the abrasive particle when there is no rotation for the magnets.

At the same pressure that is 37.5 bar helical length of travel in case of MRAFF is 43.5 millimeter and which is lesser than R- MRAFF process. Hence, lesser polishing then MRAFF, I am sorry it is not double but it is one and a half times what you get at 250 rpm as compared to the axial or only MRAFF process which is 43.5 millimeter.

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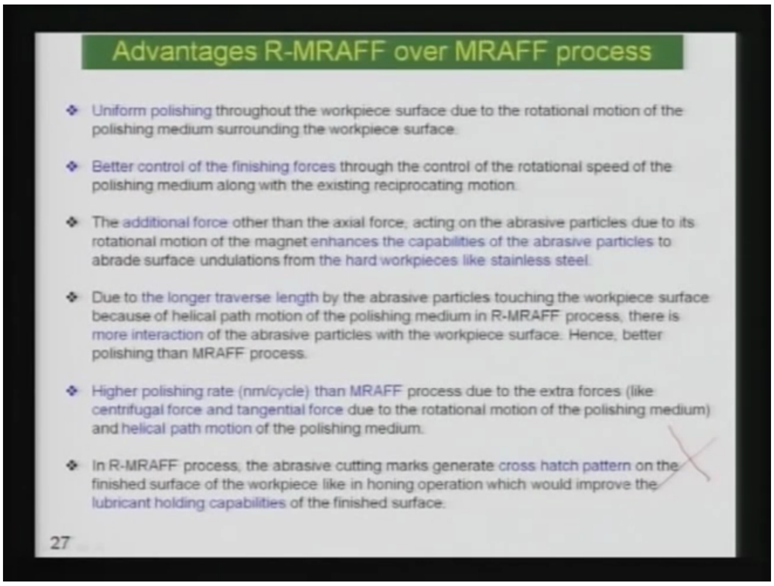

Advantages of R- MRAFF process over MRAFF process, uniform polishing throughout the work piece surface due to the rotational motion of the polishing medium surrounding the work piece surface then better control of the finishing forces through the control of the rotational speed of the polishing medium along with the existing reciprocating motion due to the hydraulic unit.

The additional force other than the axial force, acting on the abrasive particles due to its rotational motion of the magnet enhances the table is of the abrasive particles to abrade surface undulations from the hard work pieces like stainless steel. Due to the longer traverse length by the abrasive articles touching the work piece surface because of the helical path motion of the polishing medium in R- MRAFF which I have already explained, there is more interaction of abrasive articles with the work piece surface. Hence better polishing then MRAFF process is achieved, also the finishing rate is also enhanced.

Higher polishing rate or finishing rate in terms of nanometer per cycle as compared to MRAFF process due to the extra forces like centrifugal force and tangential force due to the rotational motion of the polishing medium and helical path motion of the polishing medium are obtained. In R- MRAFF process, the abrasive cutting marks generate crosshatch pattern which I have already shown to you something like this. I will show you some pictures also on the finished surface of the work piece like in honing operation, traditional honing operation which would improve the lubricant holding capabilities of the finished surface and this is an important property in certain applications.

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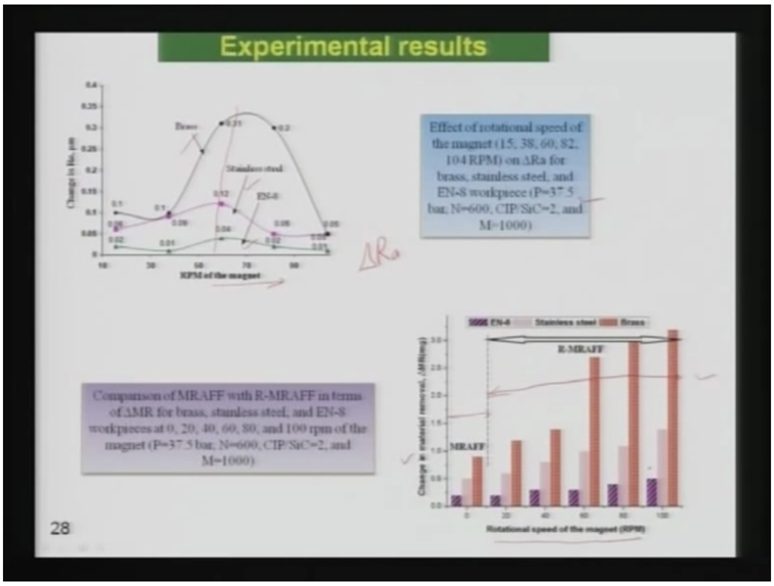

Now you can see the experimental results over here, the change in Ra that is Delta Ra which is nothing but the (()) (51:03) Ra value minus final Ra value or finished surface Ra value, you can see 3 cases have been analyzed here rpm of the magnet is changing and here is the case of brass, stainless steel and EN8, 3 different work pieces were taken, 2 of them are non-magnetic, one of them is magnetic that is where EN 8 steel and you can see some details are given here, effect of rotational speed of the magnet and it was varied along like this on Delta Ra or brass stainless steel and EN8 work piece surface other conditions are given there.

Now one thing you can see here that almost in all the 3 cases there is some rpm where you are getting the maximum change in Ra value beyond which it starts decreasing. Now here again it gives the comparison of MRAFF and R- MRAFF process, if we see on the last figure this is the change in material removal Delta MR in terms of milligram and it is low in case of this MRAFF process and it is more in case of R- MRAFF process and it is continuously increasing with increase in the rpm and you can see in all the 3 work piece materials that is EN8, stainless steel and brass this value is increasing whatsoever small and in case of brass this increases maximum compared to other 2 materials.

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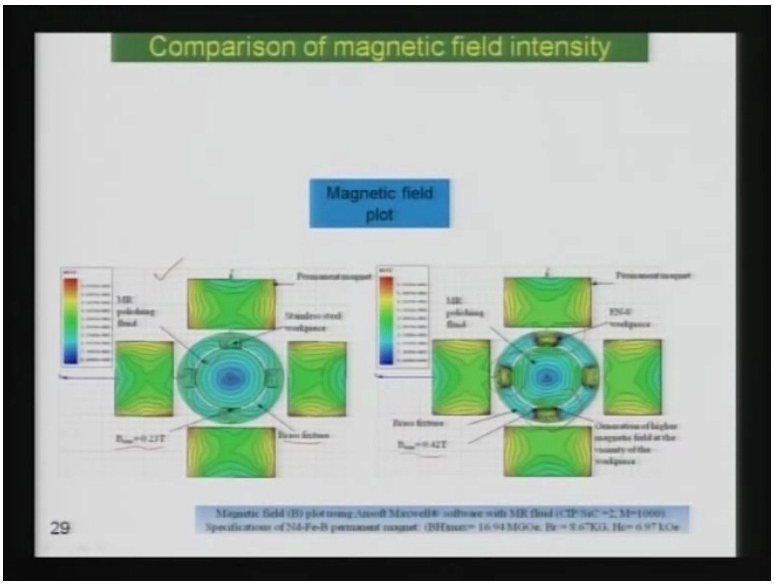

Now this is another interesting simulation that has obtained and you can see here, here are the magnetic field plot comparison of magnetic field intensity. Now you can see here this is the case where there is non-magnetic work piece material and you can see here is the magnetic MR magnetorheological polishing medium this is a stainless steel work piece, 4 work pieces are there at 90 degree and this is the brass fixture is there which is non-magnetic, if the field applied is 0.23 Tesla.

Now you can see the magnetic field is more or less uniformly distributed but if you come here on the right-hand side magnetic flux density this 0.42 Tesla flux density and important thing to note here is there is a large field intensity near to the work piece because these work pieces are magnetic materials and what happens because of this the abrasive particles penetrate inside the work and there is not enough strength of the polishing medium that they can remove whole of the material.

So either this rotates or the abrasive particles remain there intact and you do not get good surface finish in case of magnetic work piece material as compared non-magnetic material. However you can get much more faster finishing rate in case of magnetic material, if axial force is large enough to remove whole of the material from whatever large penetration you have got in case of magnetic material.

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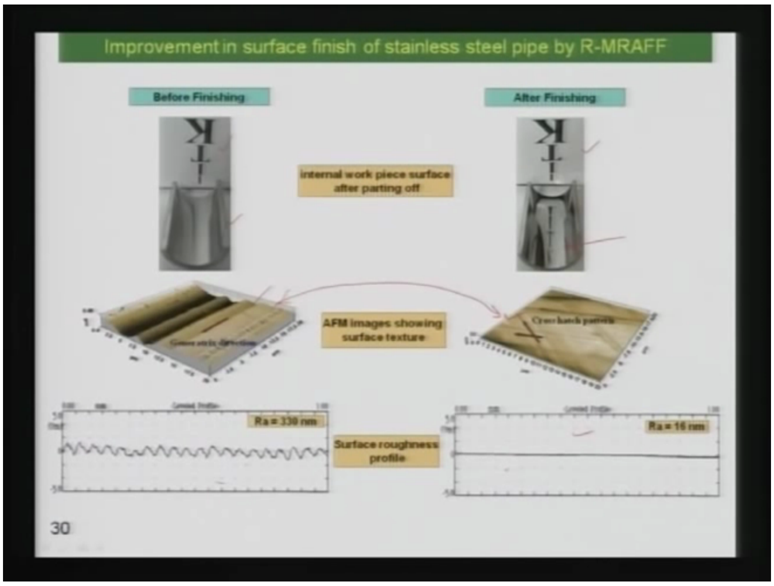

Now this is interesting figure you can see here this is the initial work piece surface before finishing you can see this is IITK written over there and this is the initial surface and this is the atomic Force micrograph and this is self analyser can see the initial surface roughness is 330 nanometer and large peaks and valleys are there and there is no reflection of the latter IITK from the unfinished work piece surface.

When you finish this work piece surface with the help of the R- MRAFF and you keep the same IITK in the inverse way you can clearly see the latter IITK reflected just like a mirror on the work piece surface and this is the crosshatch pattern that has been obtained by R-MRAFF process and this is the atomic Force micrograph that you can see clearly and you can also see the difference between these 2 graphs or the surfaces clearly and then surface roughness profile is there and if you see this surface roughness ploy of 60 nanometer and here on the left side 330 nanometers and it clearly indicates the finishing that has been achieved by R- MRAFF process.

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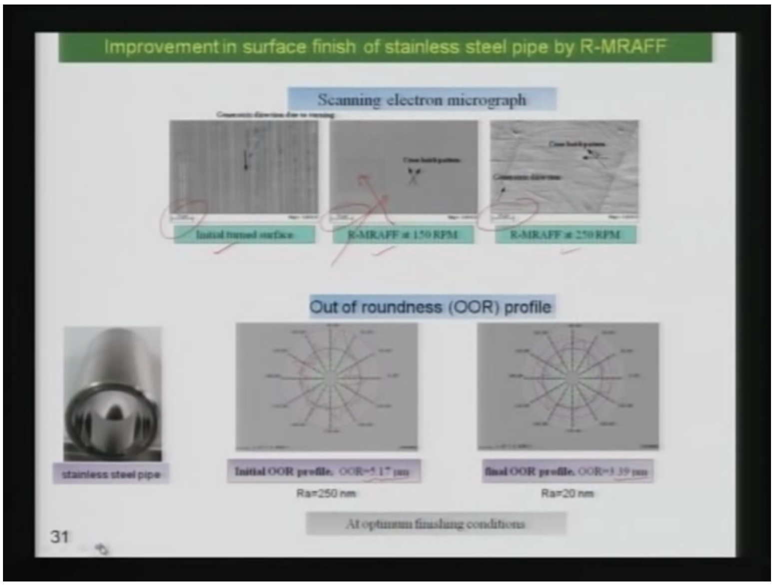

And these are the SEM photographs which indicates initial surface over here turned surface because these are the cylindrical work pieces which have been prepared on the lathe machine and here is the R- MRAFF process at 150 rpm and you can clearly see the crosshatch pattern like this as well as like this they are clearly shown over here with the help of the arrows and then R- MRAFF process at 250 rpm and there is improvement in the surface finish to some extent but crosshatch pattern still visible and these figures have been taken at high magnification you can see the scales given over here that will give you the idea for that.

Now out of roundness it is not only the finishing that you obtain out of roundness of the cylindrical work pieces is also very important. So what we did? We took the out of roundness measure of the initial work piece before finishing and then after finishing and you can see clearly initially out of roundness as 5.17 micrometers and after finishing it becomes 3.39 micrometers and it was of obtained at optimum finishing condition.

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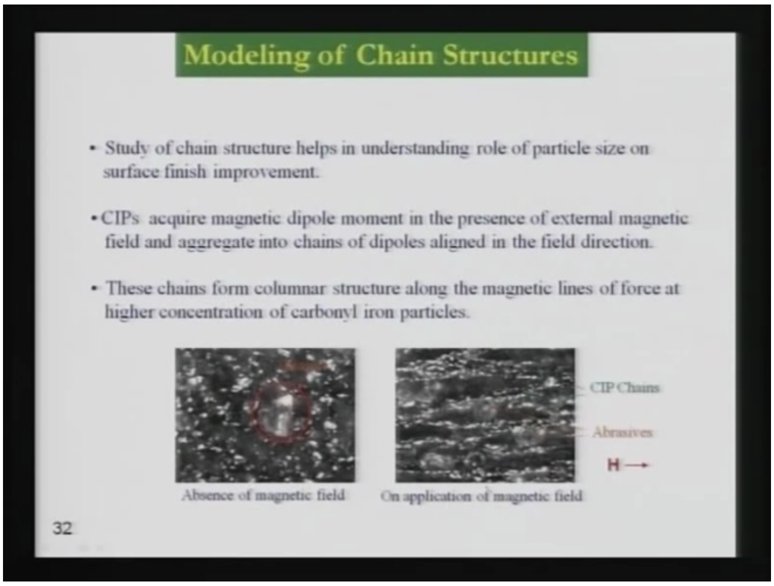

Now let us discuss the modeling of chain structure that is formed in case of MRAFF process and R- MRAFF process. This picture I have shown to you that in the absence of magnetic field the abrasive particles and Iron particles they are randomly distributed here we have taken deliberately, slightly larger abrasive particles and you can clearly see that this is the abrasive particle which is there and this is randomly distributed in the medium.

Now when we apply the magnetic field you can clearly see the difference in left-hand side figure and right-hand side figure proper chains are being formed and these are the abrasive particles between the chains that you can clearly see because abrasive particles are much bigger than the iron particles we have taken them much bigger than the iron particles, so that you can clearly see it and these abrasive particles are lying between the chains and these are the chains which are shining particles are there.

So study of chain structure helps in understanding role of particle size on surface finish improvement. CIPs acquire magnetic dipole moment in the presence of external magnetic field and aggregate into chains of dipoles aligned in the field direction as you can see here on the right-hand side figure. These chains form columnar structure along the magnetic lines of force at higher concentration of Carbonyl iron particle and this columnar structure is very important as you can see because this is the one which gives the strength or shear strength to the medium because of which it is able to remove the material.

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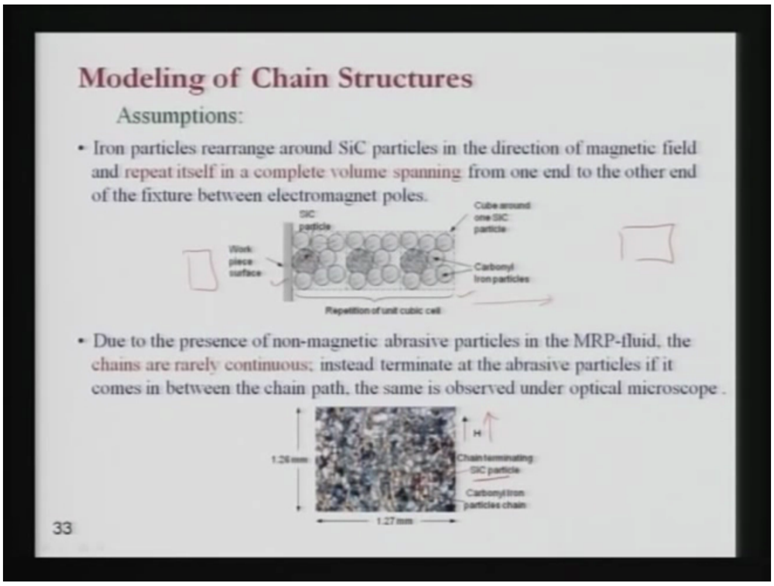

Modeling of chain structure has been done. Now this kind of chain structure has been assumed, all this will depend upon the concentration of the abrasive particle and concentration of the CIP or iron particles and here is the SiC silicon Carbide particle and these are the iron particles or Carbonyl iron particles and you can see this is the kind of the structure that has been assumed theoretically.

So iron particles rearranged around Silicon Carbide particle in the direction of magnetic field and repeat itself in a complete volume spanning from 1 end to the other end of the fixture between electromagnetic poles. Now here is the work piece on the other side also there will be the other side of the work piece and one poll will be here and another poll will be on this side and this kind of structure is repeated from one side to the power from one pole side to the another pole side.

Now again this is very interesting picture you can clearly see chain structure over there shining and this is the direction of the magnetic field and Carbonyl iron particles are shining clearly and then you can also see the Silicon Carbide particles over there and here as shown over there here the chain is terminating because silicon Carbide particle has come in between the chain of the CIP. So this way CIP can be either within the chain or sorry silicon Carbide particle maybe either within the chains or between the chains and this is very clearly shown in this particular picture. Due to the presence of non-magnetic abrasive particles in the MRP fluid the chains are rarely continuous as can be seen in this particular photograph instead terminate at the abrasive particles if it comes in between the chain path the same is observe under optical microscope over here.

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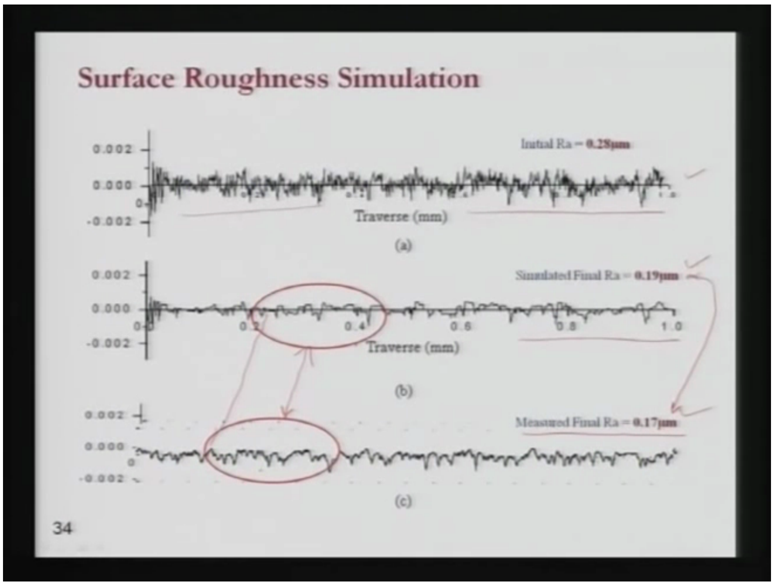

Now you can clearly see using the models which was developed at IIT Kanpur, surface roughness simulation has been done, forces were calculated and in this particular way this is the initial surface roughness that is 0.28 micrometers and this whole picture was taken from the surf analyzer data and this is showing peaks and valleys of a particular surface.

Now taking these peaks and valleys of the particular surface as an input to the assimilation software, we simulated it and you can see after simulation for certain time for which finishing was done the simulated results gave this particular output with a 0.19 micro-meter as simulated final surface roughness Ra value and this is the picture of the simulated surface and then finishing was done of the finished surface which was finished by R- MRAFF process and you can see the surface roughness value that was obtained was just 0.17 micro-meter.

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So these 2 are not very far away they are quite close to each other simulated final Ra value as well as major Ra value and if you see this, the quality of this simulation here the peaks and valleys are quite common in the major surface as well as simulated surface that simply indicates that simulation of the surface roughness is working very well because wherever peaks are there you can see, peaks are there valleys are there and they are very well go relating with the measured surface. Hence this software was very nicely, thank you very much.

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I am Malas Das I am doing Ph.D. under Professor VK Jain and Professor (()) (62:52) in rotational magnetorheological abrasive flow finishing process. Now I am going to demonstrate the experimental setup of magnetorheological abrasive flow finishing process.

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This is the experimental setup of magnetorheological abrasive flow finishing process. This setup has 4 different components, first component is that electromagnet and this cord material and second component is a hydraulic cylinder and medium cylinder and third component is the work piece and work piece fixture and fourth component is the whole structure of this MRAFF setup.

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Then component of magneto rheological abrasive flow finishing process is the electromagnet, these are the 2 coils of electromagnet and these are the core materials and I am explaining the electromagnet. The electromagnet the design is made in such a way that it can generate 1 Tesla magnetic field, the dimension of this electromagnet is 160 millimeter and length is 150 millimeter and it is a hollow electric magnet is made of copper coil, coil has 2000 turn and it has 17 (()) (64:01) copper (()) (64:05).

This electromagnet is designed in such a way that it can generate 1 Tesla magnetic field and it can take up to 10 ampere, the code material of this electro magnet it is made of cold (()) (64:19) steel the market name of this code material is (()) (64:22).

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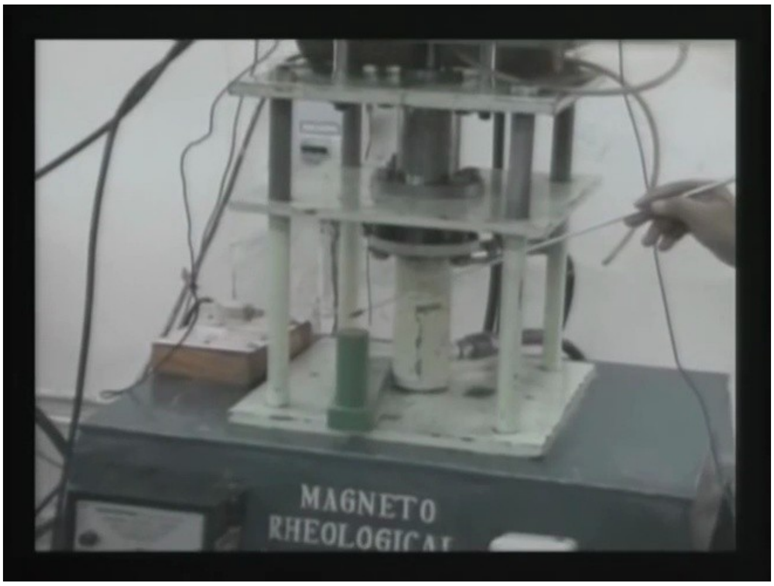

It has 2 cylindrical cross-sectional cores which is inserted inside.

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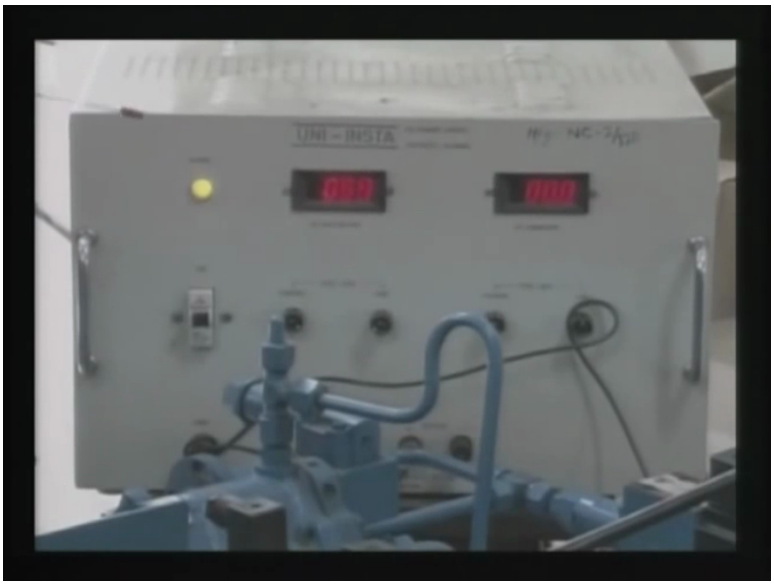

This is the DC power source of electromagnet it can generate up to 10 ampere current to the electromagnet, part of this magneto rheological abrasive flow finishing process is that hydraulic cylinder and this is the medium cylinder and these 2 cylinders are there in the top side and these 2 cylinders are there in the bottom side also, this is a hydraulic cylinder and this is the medium cylinder.

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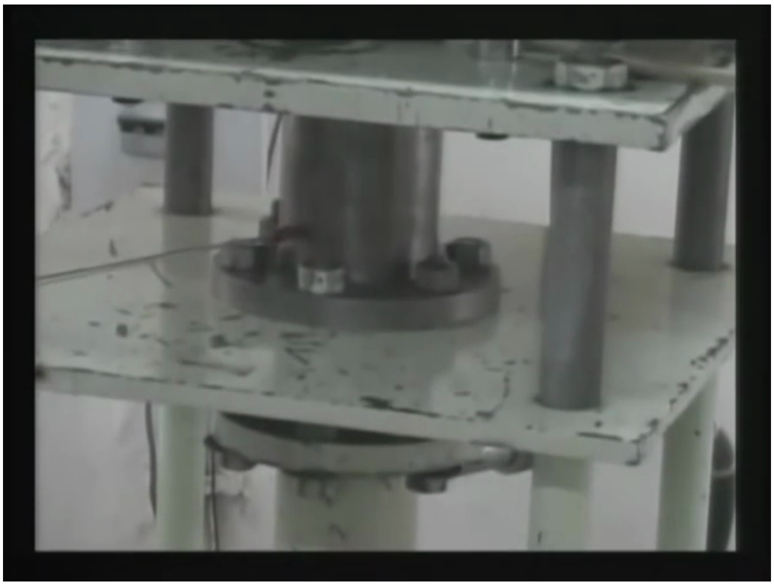

This is work piece fixture of MRAFF process it has 3 parts, the top guiding attachment is there to flow the polishing media from the top media cylinder to the work piece fixture, finishing zone of the magneto rheological abrasive flow finishing process this work is fixture is made of brass materials it has 4 internal slots to fix the work pieces.

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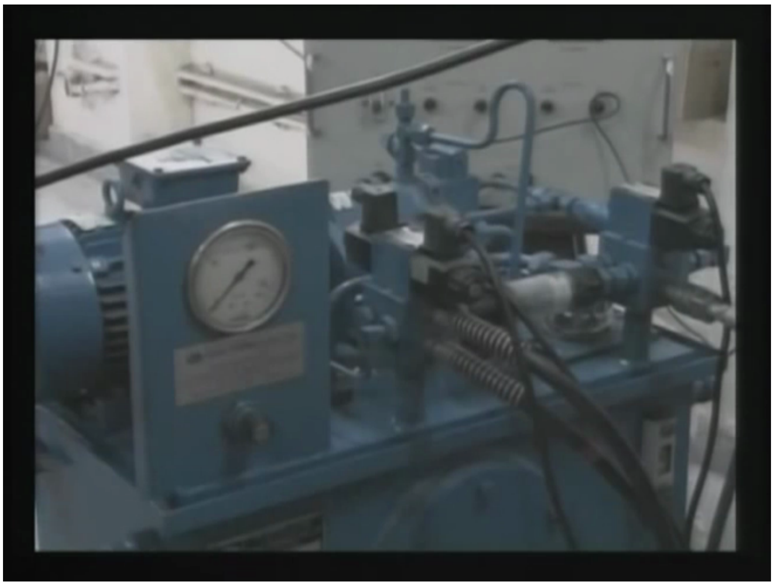

This is the hydraulic unit of MRAFF process who is provided the pressure to the piston of MRAFF process, this is entry and this is the exit of the hydraulic fluid of MRAFF process is it has a direction control valve which is committed to the solenoid and it changes the direction of the fluid in the MRAFF setup, so that it can generate reciprocating means from the top grade Centre to the bottom grade Centre then the fluid will come from the bottom grade Centre to the top grade Centre.

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This is the hydraulic cylinder and this is the medium cylinder, inside this hydraulic cylinder 1 piston is there an inside this medium cylinder 1 Teflon piston is there and these 2 pistons are connect it by a collecting rod when this hydraulic pump is activated at that time this hydraulic fluid will come to the top entry of the pipe and it will press the piston in the hydraulic cylinder then the fluid will come back to the bottom pipe and it will come to the lower hydraulic unit, all these process reciprocating motion can be provided in the MRAFF process.

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1 Teflon piston is inserted inside this medium cylinder and inside this medium cylinder 1 stainless steel liner is kept. 1 counter is attached to the MRAFF setup it is provided to count the finishing cycle of MRAFF process.

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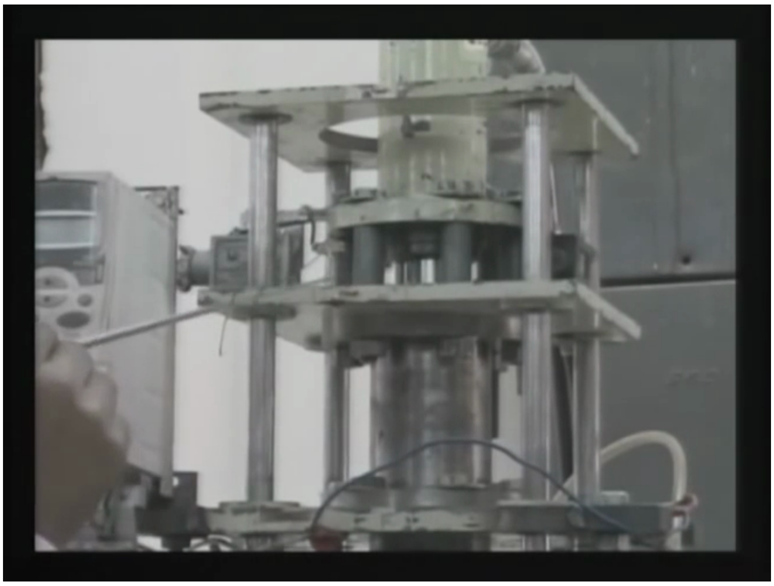

Now I am showing the houses reciprocating motion is provided in the MRAFF setup and this is the limit switch which is attached to the piston of medium cylinder and it changes the current to the hydraulic unit and the flow of fluid is reversed, the purpose of this limit switch is that it controls the stroke length of the piston in the medium cylinder.

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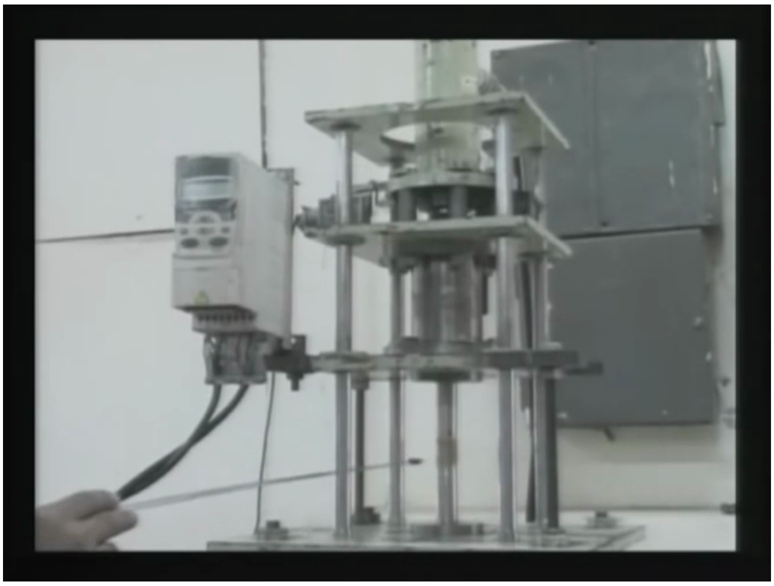

This is the work is fixture of MRAFF process, it has 2 pads, one pad is the top guiding attachment which is committed to the top medium cylinder and another part is the bottom guiding attachment which is connected to the bottom medium cylinder, inside these 2 guiding attachment 1 brass fixture is attached and inside this brass fixture 4internal slots are there or flat work pieces are kept and electromagnets cores are attached at these 2 points.

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Now I am showing how this reciprocating motion is provided to the Teflon piston inside the medium cylinder. See this piston is reciprocating inside this medium cylinder at the bottom; this is the bottom medium cylinder.

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Now piston is given reciprocating motion to the top medium cylinder also and these reciprocating motion of these 2 pistons are synchronized by a limit switch.

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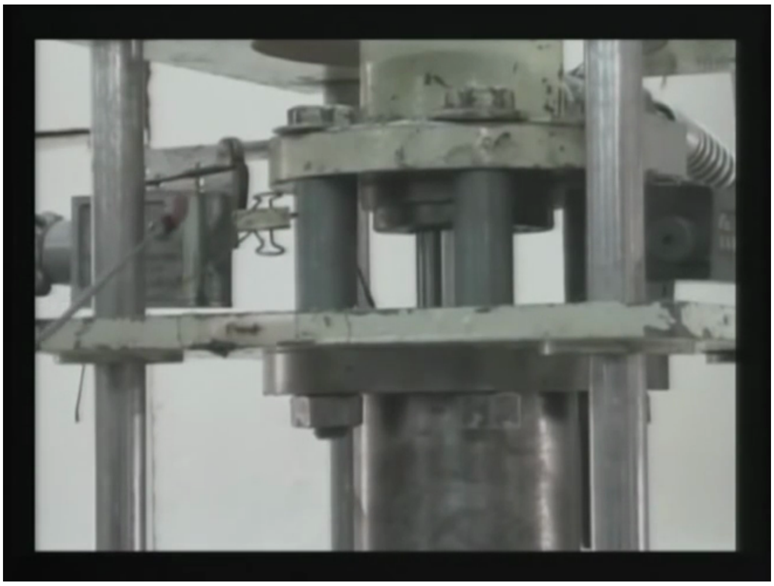

The changes of the direction of the piston is controlled by a limit switch, see how this limits which is activated now and after this activation the direction of the piston is reversed.

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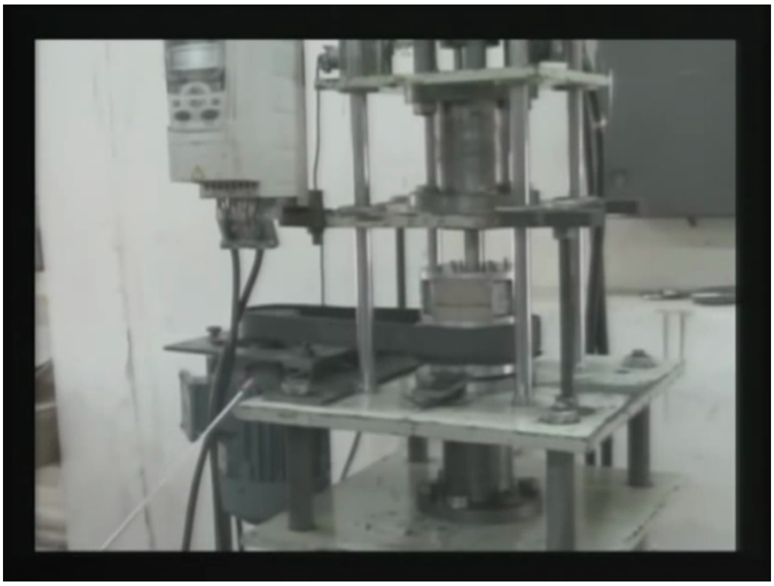

Main problem of MRAFF process is non-uniform finishing of the work piece and also due to the reciprocating motion the abrasive particles comes in contact in a straight line part. So to increase the finishing efficiency or MRAFF process and to uniformly polish the work pieces rotational magneto rheological abrasive flow finishing is evolved.

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In rotational magneto rheological abrasive flow finishing process permanent magnets are used, these are the permanent magnets which is here are permanent magnets, the scientific name of this permanent magnet is Neodymium, iron, boron these types of 4 permanent magnets are attached to this magnet fixture, this magnet fixture is connected to this pulley and this pulley is connected to this motor via a positive belt drive.

In R- MRAFF process this magnetic field is rotated via a permanent magnet and this rotation is provided by a AC synchronous motor and the rotational speed of this motor is controlled via a variable frequency drive. The accuracy of this drive is 2 RPM, see how these permanent magnets are rotated through a fixture and inside this work piece fixture the polishing media is given reciprocating motion. So there are 2 motions are there, one is this reciprocating motion and another is that rotational motion.

MRAFF process consists of magneto rheological polishing media, magneto rheological polishing media consist of 4 different parts, first part is the base media and base media consist of paraffin oil and grease. Instead of paraffin oil we can use also silicon oil and grease is used to increase the viscosity of the polishing media and it reduce the sedimentation problem of MRAFF process. The second part is the iron particles, iron particles are 2 types it can be Carbonyl iron particle or it can be electrolyte iron particles.

People all over the world are using Carbonyl iron particles CIP particles, it is manufactured BASF Germany and this is the electrolytic carbon particles it has bigger size 250 to 300 mesh size apart of magneto rheological polishing in India is abrasive particles. Abrasive particles are maybe black silicon Carbide or boron carbide or aluminum also can be used.

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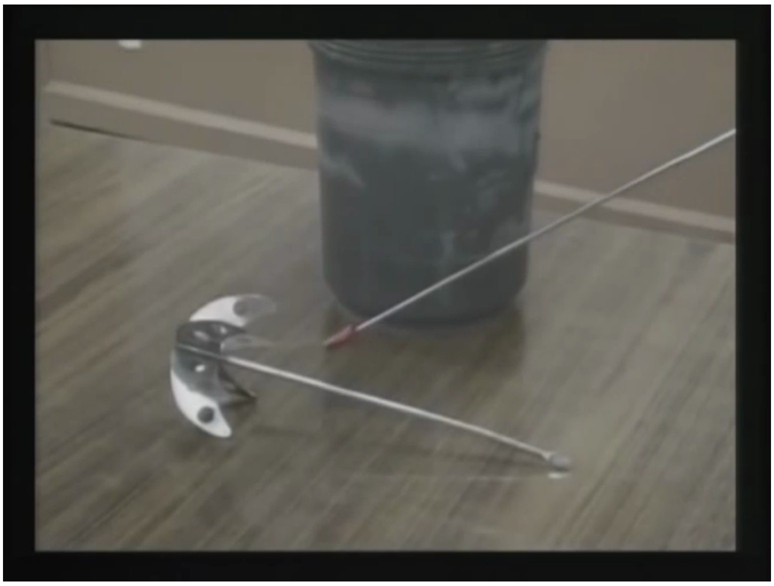
Magneto rheological polishing medium is prepared in this trigger and this is a container where this polishing medium is prepared. Initially is best medium like paraffin oil and grease is put inside this container and it is stirred for half an hour then iron particles is put inside this container and it is stirred for another half an hour and then abrasive particles are put inside this container and this is stirred for another half an hour.

(Refer Slide Time: 72:16)



This is the especially designed blade which is used for stirring of polishing material.

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This especially designed blade is connected to this trigger and this trigger can be rotated at any RPM by a (()) (72:29). By this way a homogeneous mixture of magneto rheological polishing medium is prepared inside this container.

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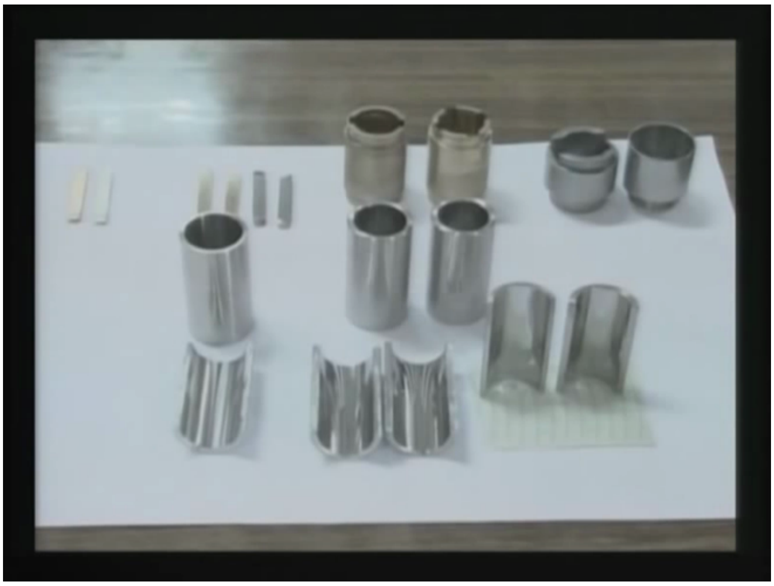

Different types of work pieces are finished by MRAFF process, one is this flat work piece, another is cylindrical work piece, this is the initial service of cylindrical work piece which is finished by R- MRAFF process, after finishing you can see the internal surface of cylindrical stainless steel work piece. This is the cylindrical work piece fixture to fix the flat work pieces it has 2 slots or 4 slots to fix the flat work pieces and this is the fixture for fixing the squares size flat work pieces.

Magneto rheological abrasive flow finishing process is evolved as a new polishing process for finishing metallic work pieces, surface (()) (73:30) from cylindrical stainless steel work pieces, thank you.