Advanced Machining Processes
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Module - 04
Lecture - 10
Magnetorheological Abrasive Flow Finishing (Part II)

So now we are going to start the rheological characterization of magnetorheological polishing fluid.

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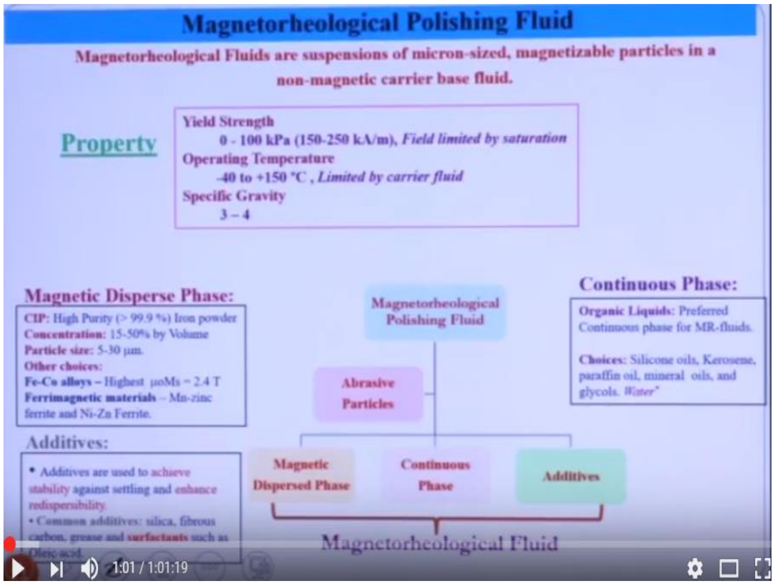

So now what are the components of MRAFF MR polishing fluid. So it consist of CIP particles, abrasive particles, and base media. So first part we do we prepare the base media. So base media it consist of paraffin oil and AP3 grease. So with certain composition, so initially we have started with 80% by weight of this paraffin oil and then 20% by weight of this AP3 grease. We mix it and homogeneously mix it for a long time for many hours, several hours to make a homogeneous mixture.

After that we mix this CIP particles, carbonyl iron particles for long time so that it can generate a homogenous mixture so that it can generate a homogeneous mixture okay. So now this (()) (1:21) fluid is prepared with a base media, paraffin oil base media. Now what we do, we mix abrasive particles there. So when we start stirring it for a long time so we have a stirring machine so on that stirring machine it is rotated, this fluid is actually mixed for a longer time okay so in a stirrer. So for several hours actually it is rotated. Then after mixing this abrasive particles it will become magnetorheological polishing fluid. So these abrasive particles actually it does not have any magnetic property. So only that CIP particles it has magnetic property. So this magnetorheological polishing fluids, magnetic property it is different than this normal MR fluid. Because this abrasive particles it does not have a magnetic property. When this abrasive particles it come into the in a in a line from when this abrasive particles comes along a chain path so this chain structure actually breaks there okay.

So we can see under microscope so this chains CIP particles chains are not continuous chain. When abrasive particles comes here so this chains break okay. So there is very few papers available in the literature who means who has taken consideration of this magnetorheological polishing fluid. Because this abrasive particles what happens it will erode the, wear out the surfaces of the rheometer. So components of the rheometer so that is why many people avoid that. So it can be this experiments can be conducted by taking proper precautions.

So now this phase different phase already we have discussed. This magnetic dispersed phase, continuous base medium phase, and then this additives and then we have added the abrasive particles there. Synthesis of MR polishing fluid, already we have discussed.

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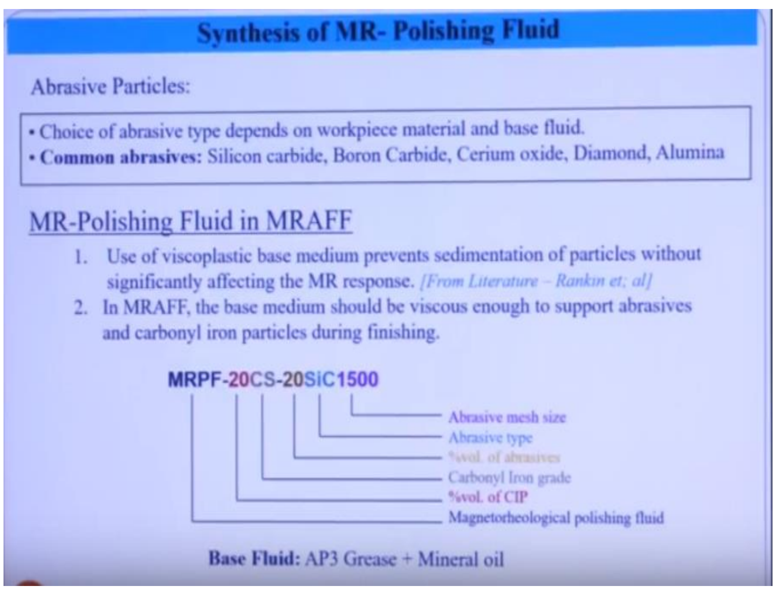

So this is MR polishing fluid, 20% by volume CS grade 20% by volume silicon carbide with 1500 mesh size and then common abrasive particles are silicon carbide, boron carbide, cerium oxide, diamond, alumina. So choice of abrasives are depend on the, depends on the workpiece and workpiece material and hardness of this workpiece material. So base media is prepared by using AP3 grease and mineral oil. So we have used paraffin oil. You can use silicon oil also okay.

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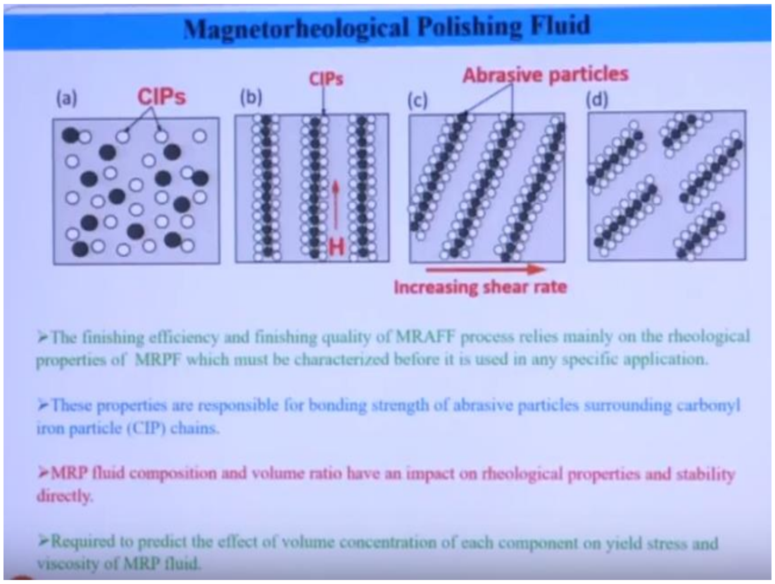

So magnetorheological polishing fluid here this schematically it is shown. When we are not applying any magnetic field here this CIP particles and abrasive particles are randomly distributed here, homogeneously it is randomly distributed. Now suppose you are applying some magnetic field, then immediately this CIP particles are forming chains. So this kind of long chains are actually forming.

So outside these are the CIP particles and inside this abrasive particles. So abrasive particles are held in between this chains. So we are trying to show this schematically. This is not exactly the ideal phase, but we are showing how it happens. Now when you are giving some shear force here at this direction so this chains will try to rotate.

So this chains are rotating so when you are applying more shear rate this chains will rotate more and after some time what will happen this chains will break here, this chains will break when chains breaks this MR fluid does not have certain time to recombine with this within these chains okay. So that is why this MR fluid it has a shear thinning property okay. So when you are applying more shear rate your viscosity actually reduces with the with the application of high shear rate this viscosity reduces. That is why this MR fluid has a shear thinning property.

So now why you are doing this rheological experiment, because this finishing efficiency and finishing quality of MRAFF process depends on the, relies on the mainly on the rheological properties of MR fluid which must be characterized before using any specific applications. So because these rheological property means this finishing efficiency basically depends on the yield stress and viscosity of this MR polishing fluid. Because it is a non-Newtonian fluid it is it is defined by the viscosity and yield stress of this fluid okay. So finishing efficiency basically depends on the rheological properties of the MR fluid. More yield stress of this fluid, it will it has a higher strength okay.

So these properties are responsible for the bonding strength of this abrasive particles surrounding the CIP particles chains. So this more the strength of this fluid, will be more bonding strength to the abrasive particles and these abrasive particles more bonding strength are there then it will remove the certain undulations in a better way.

MRP fluid composition and volume ratio have an impact on the rheological properties of the MR fluid. So its fluid this individual components of the fluid governs the rheological properties of the magnetorheological polishing fluid. So that is why this it is required to predict the what should be the concentration of CIP particles, what should be the concentration of this abrasive particles, what should be the concentration of this grease, what should be the concentration of your base media like paraffin oil okay. So that is why we need to find out what should be the concentration of different elements of this MR fluid.

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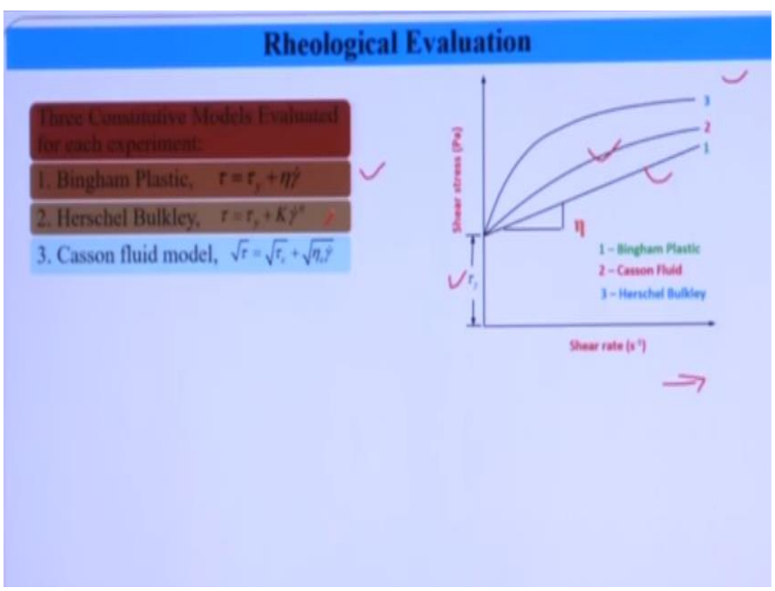

So MR magnetorheological fluid actually it is represented by 3 different models. All these are actually non-Newtonian model. So first one is the most popular, this is called Bingham plastic model. In Bingham plastic model you can see tau equal to shear stress tau y plus eta into gamma dot. So tau y is the yield stress of this fluid tau is the applied shear stress eta is the plastic viscosity and gamma dot is the shear rate. So in x axis it is shear rate and in y axis it is shear stress. So this one is the Bingham plastic fluid. So it has a certain yield stress. When applied shear stress is greater than this yield stress of this fluid then only this fluid flows otherwise this fluid does not flow.

The second one is the Herschel Bulkley fluid sorry Casson fluid, second one is the Casson fluid here. So this Casson fluid actually it is represented by root tau equal to root over tau c plus root over eta c and gamma dot. Here tau also same as applied shear stress and gamma dot is the shear rate tau c is the yield stress and eta c is the plastic viscosity here. Also MR fluid can be represented by their most popular which is Herschel Bulkley fluid. Herschel Bulkley fluid can be represented as tau equal to tau equal to tau y plus k into gamma to the gamma dot to the power l.

So these are the different fluids are there. So in Herschel Bulkley fluid this n actually governs this consistency index it governs whether it is shear thickening, whether it is shear thinning, or whether it is normal Bingham plastic fluid. So in Herschel Bulkley fluid if you put this n equal to 1 then it will become the normal Bingham plastic fluid. When n is greater than 1 then it is shear thickening fluid means its viscosity increases with the increase in the shear rate and when n is less than 1 it is shear thinning fluid.

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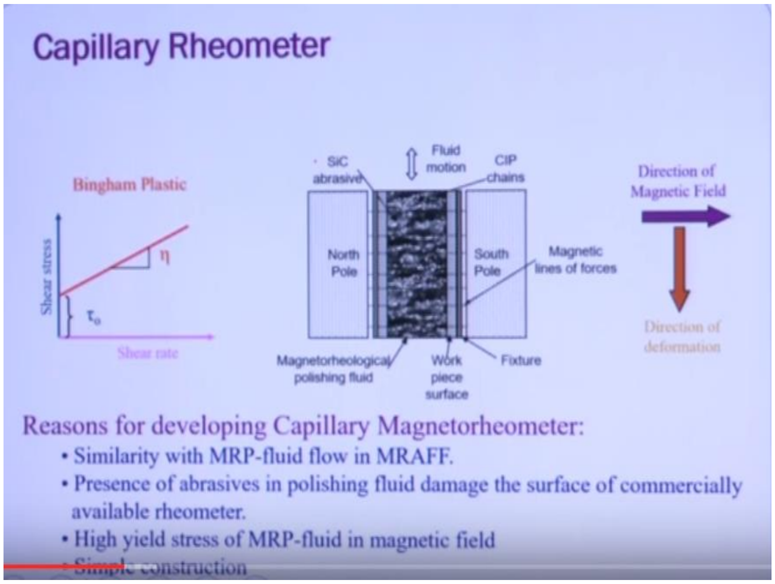

So different rheometers are actually tried. Initially we have tried with capillary rheometer. So the advantage of using capillary rheometer is that it is very cheap to make and it is easy to make also and easy to use also. So here in our and it has a certain similarity. It has a similarity like our finishing process MRAFF finishing process. Like in MRAFF process this is the direction of the field, magnetic field and we are flowing the deformation direction we are flowing the fluid in the vertical direction and in the vertical direction we apply the magnetic field in case of MRAFF process.

So here you can see that the CIP chain structures are there. So these chains are forming horizontally. Now we are flowing this fluid along this vertical direction okay. So these are the reasons for developing the capillary magnetometer. Similarity with the MRP fluid flow in MRAFF. Presence of abrasives in polishing fluid damage the surface of the commercially available rheometer. High yield stress of MRP fluid in magnetic field and then simple in construction this capillary rheometer.

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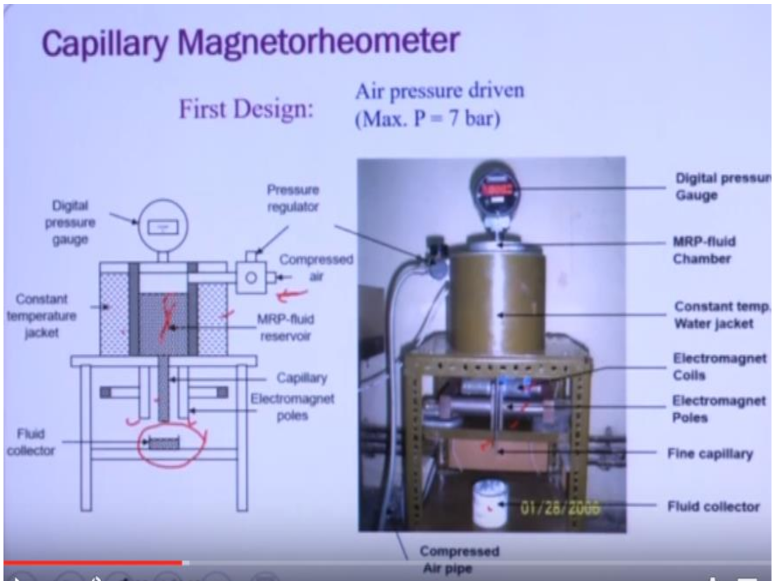

So you can see this first design of that capillary rheometer. So this is the container here. So constant temperature jacket is actually it is kept here so that this temperature of this MR fluid can be maintained in this jacket in this container, this temperature can be maintained here. So it is filled up with the MR polishing fluid here okay. So this is the capillary tube. It is attached just bottom at the bottom of this container okay. Now you can see this is the core material of this magnet. It has to be certain maintain certain ratio, l by t ratio should be more than 0.4. So here diameter of this tube it is 2 mm here internal diameter of this tube is capillary tube is 2 mm okay. So length of this flat 2 flat actually plates are actually fixed just outside this capillary tube. So the length of this capillary flat plate is 60 mm okay.

So there is a container is there to collect the MR fluid which is coming outside this coming through the capillary tube after steady state is reached, obviously it is after steady state is reached. So this MR fluid is flown by using a compressed air. So this there is a compressed air at entry here so through this compressed air is coming. So there is a gauge is there, pressure gauge, digital pressure gauge. From this pressure gauge actually you can measure the whatever the pressures are there inside that container, MR fluid container okay.

So this is the electromagnet here. This is the core material of this electromagnet. In front of the core material 2 flat plates are actually fixed and this is the capillary here and this is the container to collect the MR fluid just below the capillary. So this can sustain up to pressure of 7 bar because when we have started doing experiment using this rheometer what we have seen that because of we are using compressed air so it is making a hollow channel inside this MR fluid okay. So it is very means it is very difficult to maintain a uniform pressure just above the MR fluid layer okay.

So it is very difficult to maintain uniform pressure inside the container. So that is why this design is discarded and then we have developed one more design so we can show we shall show here. So it is we have used our similar setup of MRAFF setup for measuring the viscosity of this polishing fluid. We have used the similar setup for measuring the viscosity of this polishing fluid.

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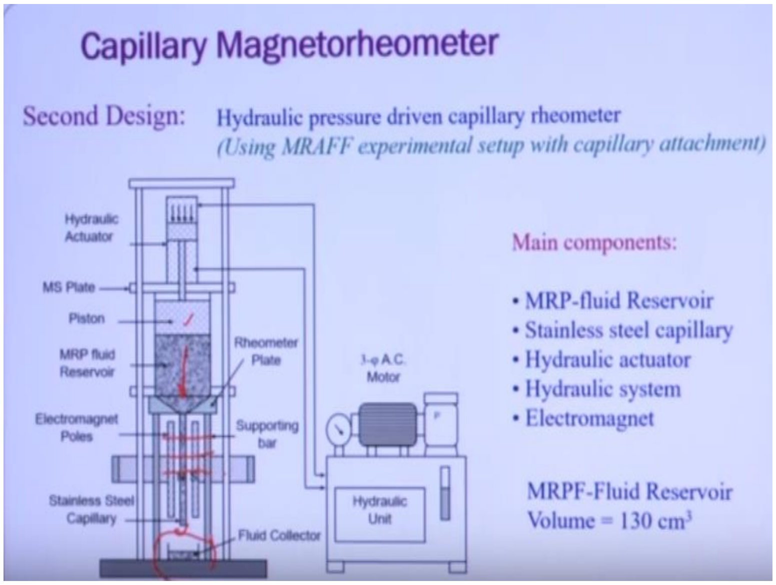

Here what we have done this is the capillary here, just outside this capillary we kept this magnet electromagnet here and this MR fluid actually it is flown by this hydraulic unit. So this is the piston here, MR fluid piston. So it is MR fluid is flown through this hydraulic unit okay. So this is the top media cylinder. So initially this top media cylinder is filled up with MR fluid. Now after that this total attachment is attached, this total attachment is attached to this top media cylinder okay. Just below that we have fixed our this capillary tube and just outside this capillary tube we kept this 2 plates for applying this magnetic field okay.

So in this configuration so advantage is that we can measure the viscosity of this polishing media in the same setup and here our magnetic field, direction of this magnetic field, this is the direction of this magnetic fluid and MR fluid is flowing in this vertical direction. So we have to measure the viscosity of this fluid so that this fluid deformation, shear direction and also this magnetic field direction should be perpendicular to each other.

So this is the container here. Here you can collect the MR fluid. After this MR fluid inside this capillary has come to a steady state condition and you have to collect the MR fluid after that steady state condition inside this container here and you have to measure the time. So from this, from this time and from the weight and from the density of this MR fluid, if you know the density of this MR fluid okay, so you can calculate the volumetric flow rate of this MR fluid that is Q volumetric flow rate of MR fluid. So that is millimeter cube per second.

So this is the volumetric flow rate of MR fluid you can calculate. So only thing you have to calculate here volumetric flow rate and at the same time we know the pressure, how much pressure we have given from the hydraulic unit. So we know the pressure difference, pressure gradient across the capillary and we know the volumetric flow rate and if we know these 2 parameter we can calculate the yield stress and viscosity of this fluid using this capillary rheometer.

So this container it contains 130 cm cube. So here this MR fluid container it contains 130 cm cube or cubic cm of fluid.

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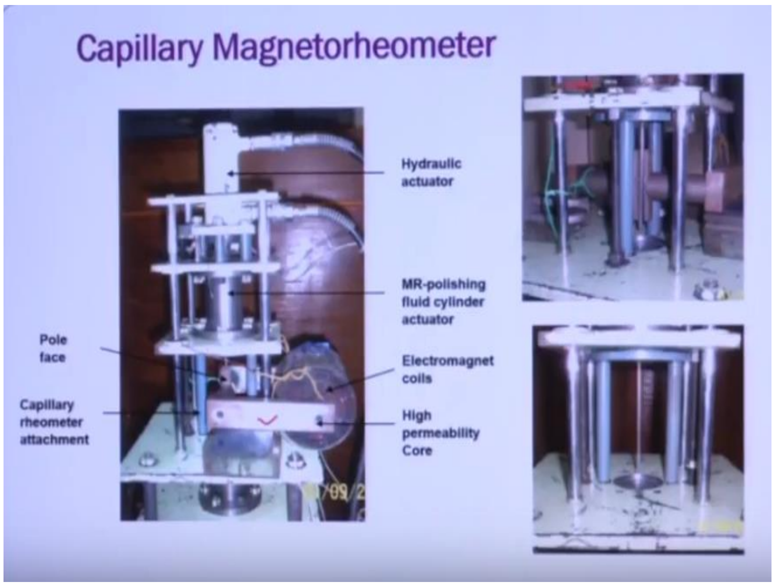

So this is the experimental setup, same experimental setup of MRAFF process is used for capillary rheometer. Here you can see this is the magnet, C type magnets are used. So this is the magnet and this is the core material here. In front of that core material you can see 2 plates are actually kept and this is the capillary here and into this portion, at this portion only here. So at this portion only this magnetic field is applied using this 2 flat plates which is attached to the core material. So we can collect the polishing media here just below this capillary for a certain time after it is reached to the steady state condition.

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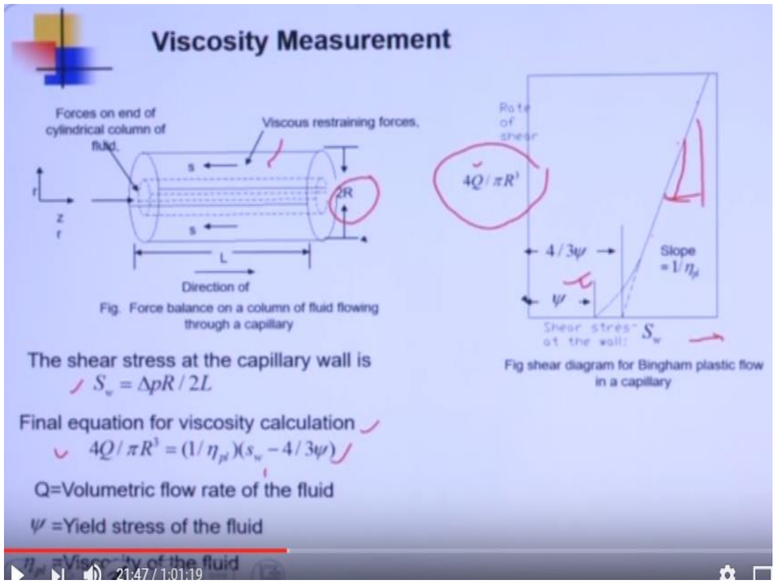

So this is the calculations. So this is the cylindrical capillary it is shown. This is the shear stress here. So this is the length, L is the length of this capillary. So in our case L is the length over which magnetic field we are applying the magnetic field, 2R is the diameter of this capillary. In our case we had considered 2 millimeter diameter of this capillary tube through which we have flown the MR fluid and shear stress at the wall we have calculated as it can be calculated as del p R by 2L, del p is the pressure gradient so how much pressure we are giving across the capillary so that we know from the hydraulic unit how much pressure we are giving.

R is the radius of that capillary, L is the length of the capillary over which we are applying the magnetic field and final equation for the viscosity calculation is 4Q by pi R cube, Q is the volumetric flow rate of this MR fluid after steady state is reached which we have measured during experiment, R is the radius of this capillary, eta p l is the plastic viscosity, s w is the shear stress at the wall of the capillary and psi is the yield stress of this fluid okay. So this is the equation.

So y axis is rate of shear 4Q by pi R cube and x axis it is the shear stress at the wall. So at different pressure, by changing the pressure we can get different rate of shear. So Q already we know here volumetric flow rate at different pressure we can calculate and at different pressure we can calculate what is the shear stress and what is the rate of shear 4Q by pi R cube. So by plotting these 2, rate of shear and shear stress at different pressure we will get this line.

So this line when it is we have to do a curve fitting using a line using a straight line and at this point we have to just extrapolate to this x axis y where it is extrapolated where it is touching to the x axis, that point will give the 4 by 3 psi okay and so that value of shear stress divided by 4 by 3 will give the yield stress of this fluid okay and the slope of this curve will give the slope of this curve will give the 1 by slope of this curve will give the plastic viscosity okay. So this 1 by slope of this curve slope equal to 1 by eta p l it will give the plastic viscosity okay. So this capillary visco rheometer is a very important instrument for measuring the viscosity of this MR fluid on the same MRAFF setup.

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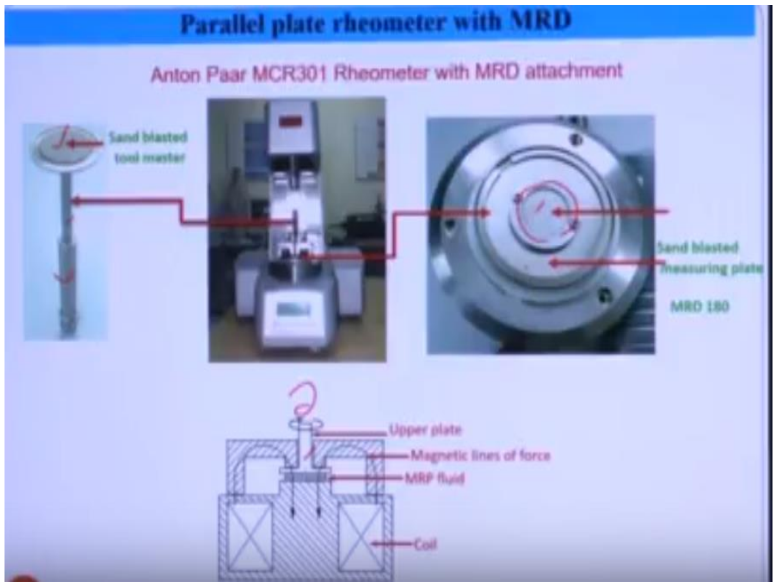

So after that we have started working on parallel plate rheometer. So Anton Paar MCR301 Rheometer is used. They have a magnetorheological device there to apply the magnetic field perpendicular to the flow direction. So this is the bottom plate here. They have 2 plate, 2 parallel plates, so this is the bottom plate which is sand blasted in our case and there is a container kind of thing so to protrusion is kept there okay.

So here actually we have to keep MR fluid so that so this diameter of this this one this bottom plate is 20 mm and this is the top plate here, this is the top plate. It is it should be kept vertically by reversing the direction, reversing its direction. So it is called tool master. So this top surface of this tool master is sand blasted. So this is the parallel plate, top plate here. This is the top plate and this is the bottom plate here.

So we are applying magnetic field just perpendicular to this parallel plates. Now we are rotating this top plate here with a certain RPM. So this RPM is proportional to the shear rate of this fluid and when you are applying some when you have applied some magnetic field and now we are trying to rotate this top plate, tool master it will generate a reversing torque, reverse torque. So this reverse torque is actually proportional to the shear stress of this fluid. So shear stress of this fluid is proportional to the torque and shear rate is proportional to the RPM of this top plate. So at different rotation, at different shear stress shear rate we will get different shear stress and these values you can plot okay.

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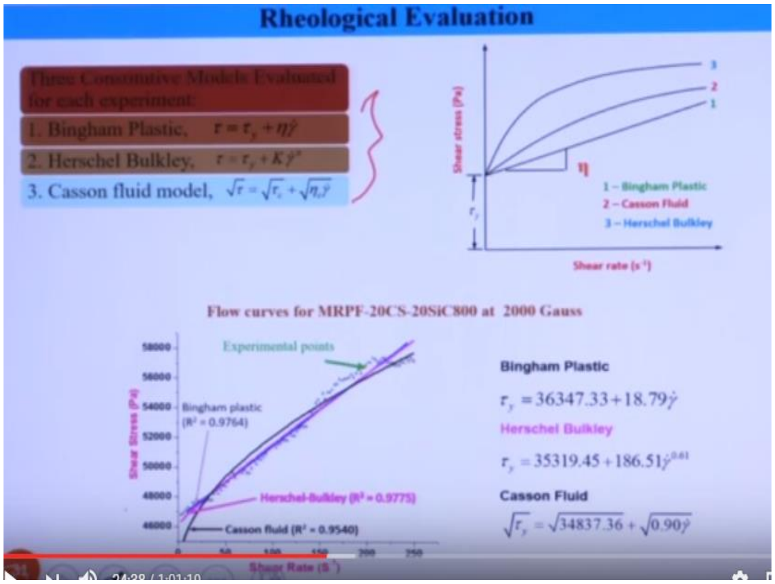

So this is the shear rate and shear stress. At different shear rate you can plot the shear stresses and these values you can connect or you can fit using a using 3 different equations which are used for modeling of magnetorheological fluid, so this Bingham plastic, Herschel Bulkley, and Casson fluid. So we have fitted these 3 equations, fitted these points using these 3 equations okay. So after fitting so we calculated the r square value for all the 3 equations. So for Herschel Bulkley, Bingham plastic, and Casson fluid model.

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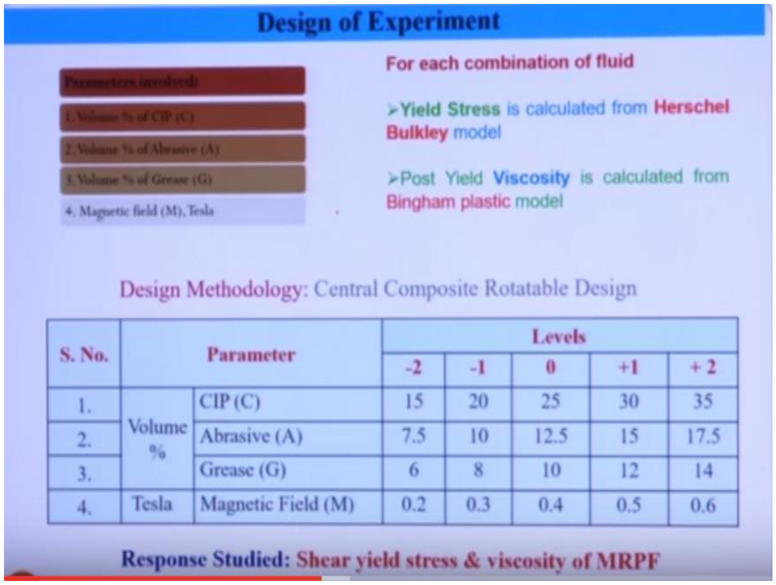

So total 30 experiments are carried out using CIP concentration of 15% to 35% so we have varied CIP particles carbonyl iron particle concentration from 15 - 35% abrasive 7.5 - 17.5%, grease 6 - 14% and magnetic field point from 0.2 - 0.6 tesla magnetic field. So these are the 4 variables are there and we have varied and experiments are carried out using central composite rotatable design and what we have measured here we have measured yield stress and viscosity of this fluid.

So after fitting these things so from this this is the Bingham plastic, this is the Herschel Bulkley and this is the Casson fluid. So you can see there so this is the yield stress from the Bingham plastic model and this is the plastic viscosity from Bingham plastic model. So from Herschel Bulkley model also you can calculate the yield stress and viscosity, from Casson fluid also you can calculate yield stress and viscosity after fitting all these points. So we have checked the yield stress and viscosity.

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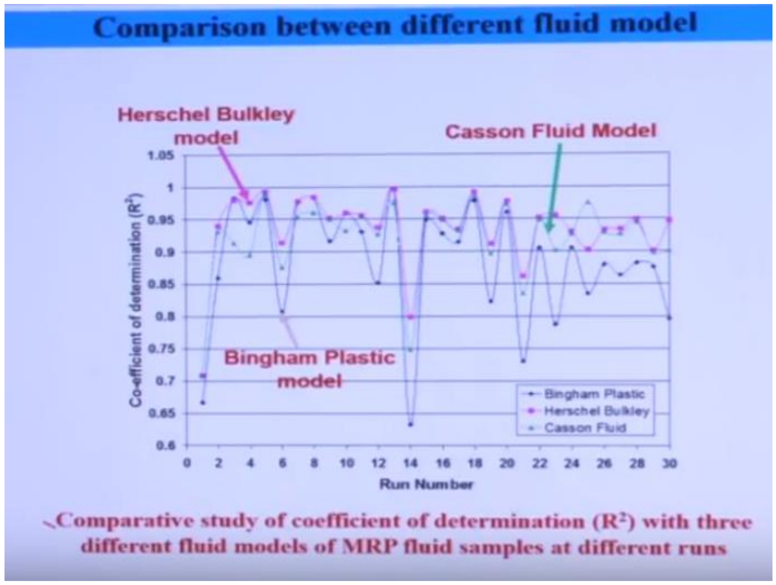

So what we found that R square value from all this all this 30 experiments we have seen that R square value is maximum for in case of R square is the nothing but is the fitting perimeter for car fitting parameter so its value is near to 1 means it is high very good fitting, 0 means very means it is very poor fitting. So in case of Herschel Bulkley model you will see we can see this R square value R square value is very high in case of Herschel Bulkley model.

So Herschel Bulkley fluid actually it fits to the data points obtained from the rheometer okay. So for that what we have done yield stress is calculated from the Herschel Bulkley model and viscosity post yield viscosity is calculated from the Bingham plastic model.

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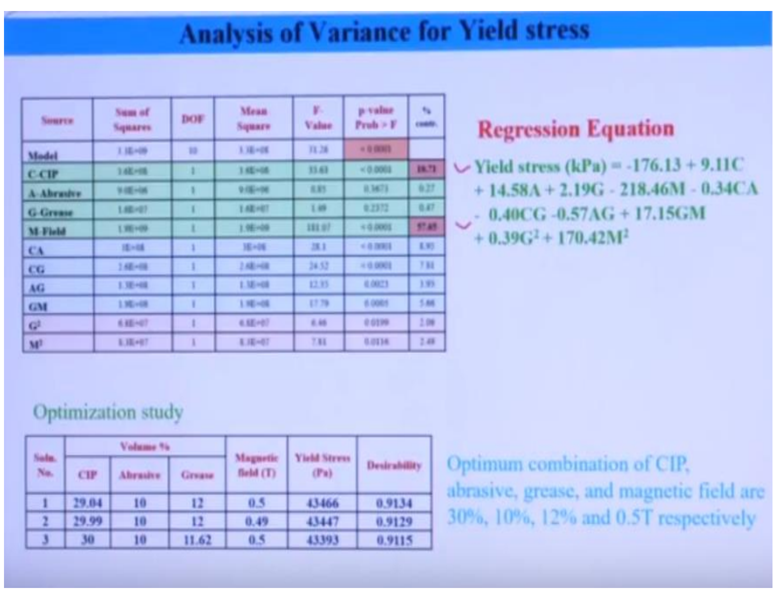

After that we have done the Anova study and we have seen that for yield stress magnetic field has the highest contribution for the yield stress then CIP particles has the least contribution and abrasive and grease they have a very less contribution. So magnetic field has a 57.65% contribution and carbonyl particles has a 10.71% contribution on yield stress of this fluid.

Then we have done the optimization study and we have found that so this 30% CIP, 10% abrasive particles, and 12% grease will give the and at 0.5 tesla magnetic field will give the highest combination which will give the highest yield stress of this fluid and this is the regression equation to calculate the yield stress.

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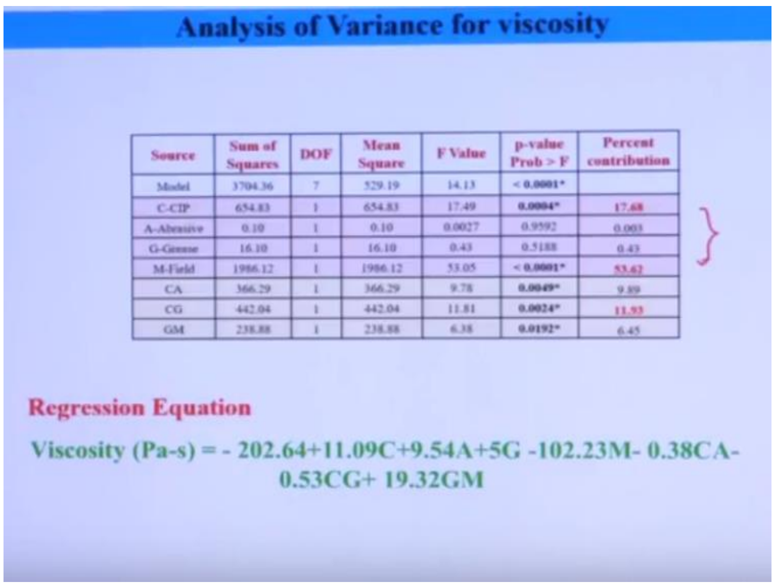

And similarly Anova is done for the viscosity model also. So what we have found that here also this magnetic field has very high contribution 53.62%, 17.68%, but abrasive and grease they do not have that much contribution okay. So this is the regression equation for the viscosity model.

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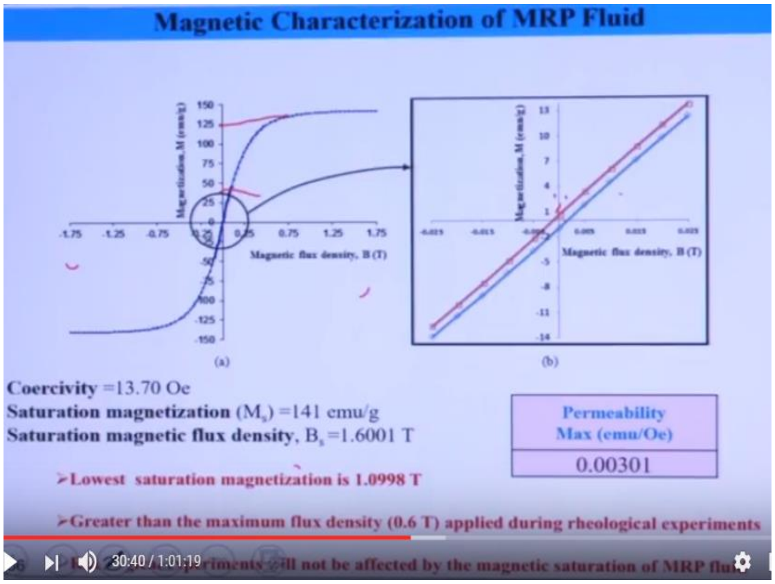

Now we have to do the after doing this rheological study we have to do the magnetic characterization also. This magnetic characterization of MRP fluid is carried out in vibrating sample magnetometer it is called VSM. So there magnetic field is varied from - 1.75 tesla to 1.75 tesla then it will come back to again - 1.75 tesla and MR fluid is kept inside a container, small container and it is run through a huge magnetic field - 1.75 to 1.75.

So now here you can see this one in this zone it is extracted here. You can see these 2 lines. One is for forward and another one is the backward okay. So this hysteresis loop you can see it has a very less remnant magnetization. Here you can see this remnant magnetization is very less. So this is the main property of the CIP particles here. So it has a very less remnant magnetization means when you are removing this magnetic field immediately whatever the CIP particles are there because it does not have any remnant magnetization it will not agglomerate. So it will immediately it will be demagnetized okay.

So there is a less chance of agglomeration in case of this MR fluid which is prepared using CIP particles. So it has a coercivity of 13.7 saturation magnetization of 141 emu/g, saturation magnetic flux density here it is 1.6 tesla and all the experimental results whatever we have shown earlier lowest saturation magnetization we have found 1.098 okay. So lowest saturation magnetization which is found 1.098 and we have applied the magnetic field as 0.6 tesla. So our rheological experiments are not affected by the magnetic saturation of the MRP fluid.

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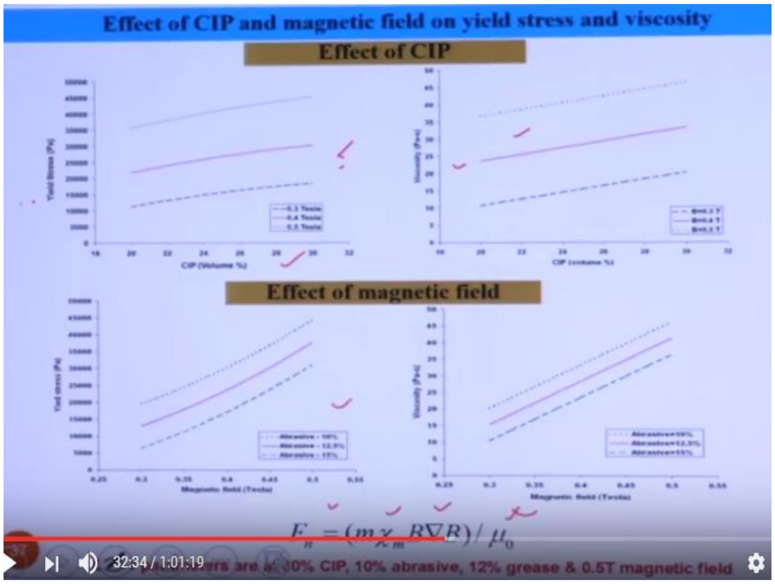

So effect of CIP and magnetic field effect of CIP concentration and magnetic field here left hand side it is yield stress and right hand side it is viscosity. You can see with the increase in the magnetic field your yield stress actually increases and with the increase in the magnetic field both yield stress and viscosity actually increases. So if you are applying more magnetic means this more strong CIP chain structures are forming. So this CIP chains will form from single columnar structure to single structure to columnar structure so it will become a very thick structure. So these abrasive particles will be held with a very higher force there.

So more bonding strength will be there, more dipole moment will be there. So that is why you will get higher yield stress and viscosity of this polishing media. So this is the force acting on a single CIP particle can be calculated as m chi m B del B by mu 0, m is the mass of this spherical abrasive particle, chi m is the mass susceptibility of this CIP particle, B is the magnetic field intensity, del B is the gradient of this magnetic field intensity mu 0 is the permeability in free space.

So all these experiments are shown here, 30% CIP, 10% abrasive, and 12% grease, and 0.5 tesla magnetic field. So with the increase in the magnetic field CIP concentration you can see both yield stress and viscosity increases. Why with the increase in CIP? CIP concentration increases means more thick structure increases, structure of this CIP chains also increases with the increase in the CIP concentration okay. So it will become more strong.

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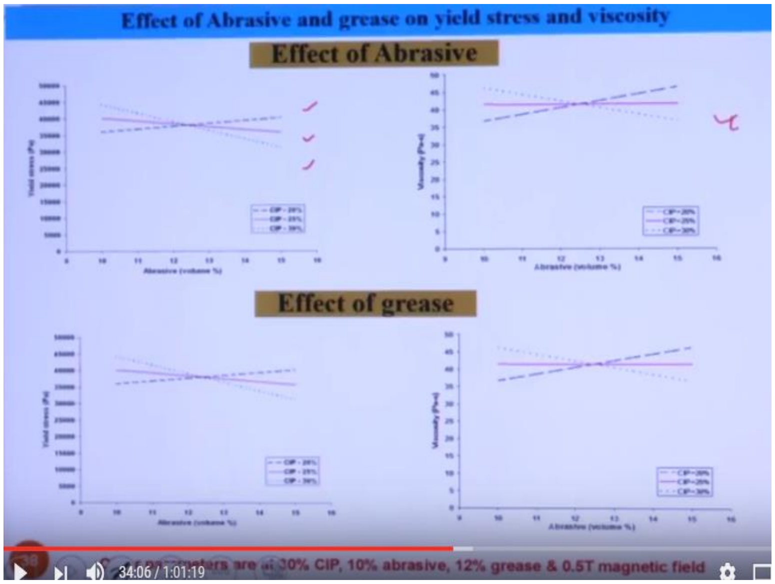

And when you are applying this abrasive particles you can see from 20% CIP so this is almost almost yield stress almost constant but at 25% to 35% you can see here this yield stress actually reduces. Similar thing actually happens for this one viscosity also. So that is why if we increase more abrasive particles there what happens these abrasive particles being a nonmagnetic in nature it does not have any magnetic property so it will when it comes in between this chain structure this its some chains are actually continuous chain, it will break into 2 pieces okay.

So this chain strength actually reduces so that is why with the increase in the abrasive particles concentration this viscosity and yield stress actually reduces and also with the increasing the grease concentration also we can see that this yield stress and viscosity of this fluid also reduces because grease actually acts as a inhibitor. For certain fixed magnetic field if we increase the grease it will resist the CIP particles to come in a chain okay. So with the increase in the grease our yield stress and viscosity of this polishing fluid also reduces.

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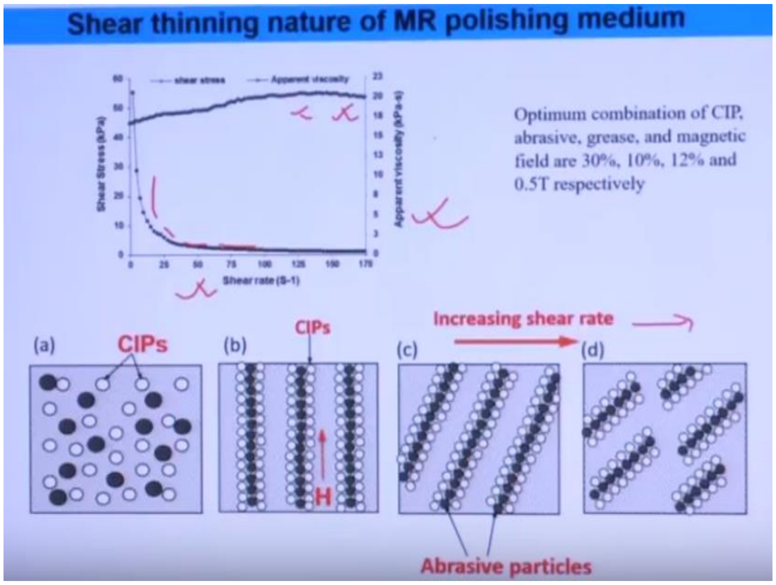

So from this figure we can see here that with the increase in the shear rate of this fluid this viscosity of this polishing fluid it is reduces drastically. So from this figure you can you can say that this MR fluid is a shear thinning fluid. So here also you can see with the increase in the shear rate of this fluid shear stress of the fluid also reduces here. So this gradient actually reduces you can say this gradient actually reduces so from this shear test profile also you can say that this MR fluid MR polishing fluid is a shear thinning fluid.

So from this schematic diagram already I have discussed this one. When we are giving increasing more shear more shear this CIP chain structure actually breaks and it has little time to recombine this to recombine so MR fluid actually behaves as a shear thinning fluid.

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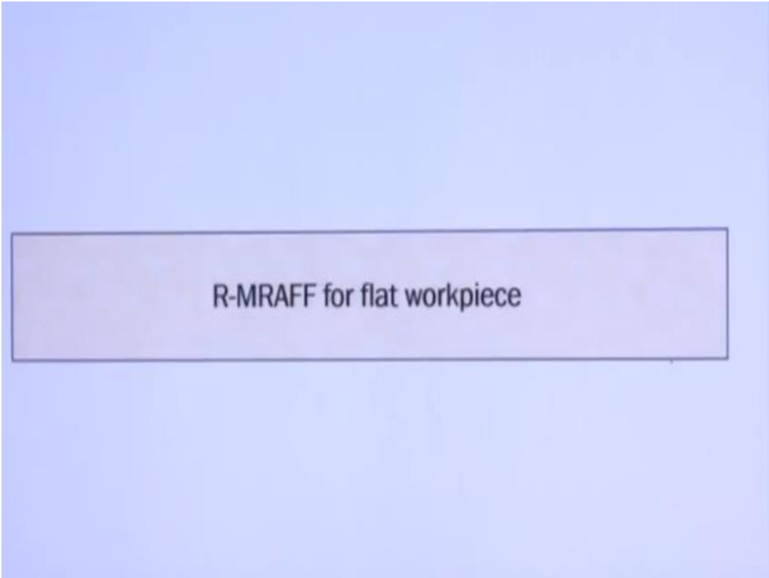

So now we shall discuss the experimental results on flat workpiece. Rotational MRAFF experimental results on flat workpiece. So we have considered flat workpieces.

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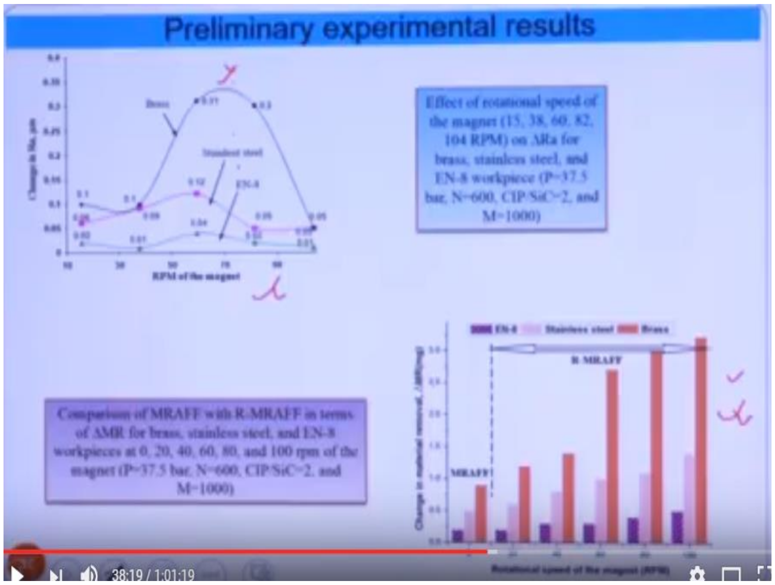

Now we have considered 3 different kinds of workpiece, one is brass, stainless steel, and then EN-8 workpiece. So this is the effect of rotational speed of this magnet. Now we can see that with the increase in the rotational speed of this magnet your change in RA means initial RA minus final RA increases and it reaches to a certain value for 3 different materials so at what point it reaches it is it gives the optimum RPM of the magnet.

So this is the optimum RPM of the magnet where change in RA is maximum. After that you can see that surface change in RA actually reduces. With the increase in the rotational speed of the magnet what happens your centrifugal force increases. So indentation into the workpiece surface increases. Also your tangential cutting force also increase and if you are increasing with a higher means with higher RPM so this abrasive particles it will it covers with the moved area into the workpiece surface, moved area of the workpiece surface so that is why your change in RA actually increases with the increase in the RPM of the magnet but beyond an beyond that optimum RPM of this magnet what happens this change in RA again reduces because we have discussed that shear thinning nature of this MR fluid so at high shear rate you are increasing RPM means you are increasing shear rate.

With high shear rate this MR fluid would not able to sustain the structure. So this chain structures actually breaks so that is why with the increase in the rotational speed of this magnet your shear means surface roughness also reduces. Now here you can see this is the change in material removal. With the increase in the rotational speed of this magnet, material removal increases. Here you can see at high RPM this material removal also increases because at high RPM because of this random penetration of this abrasive particles into the workpiece surface so material removal increases but their surface finish actually deteriorates.

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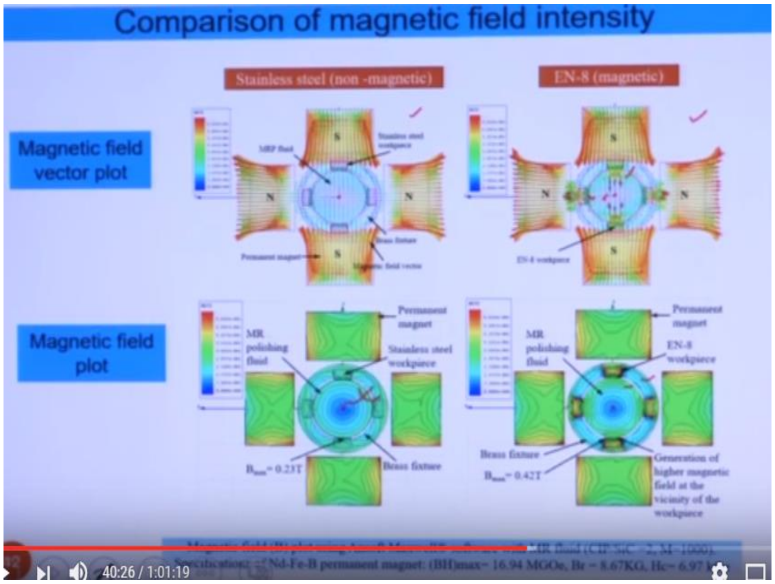

Now we can we shall discuss one more thing is that n it is the magnetic material but stainless steel we have stainless steel we have considered as nonmagnetic here. We have used nonmagnetic stainless steel, brass it is also nonmagnetic. We have seen that for magnetic EN-8 workpiece we got very less improvement in surface finish. Why it is so. So you can this magnetic field vector plot here for stainless steel workpiece and for EN-8 workpiece.

So this is these are the innate workpiece here. When you are applying some magnetic field what happens? There is a local magnetization takes place in between this magnet, magnetic pole, and the workpiece okay. So because of this local magnetization the strength of this magnetic field inside this MR fluid actually reduces and individual workpiece actually this workpiece it becomes a magnetic material and what happens whatever MR fluid has MR fluid is there it sticks into the this MR this magnetic workpieces.

For polishing actually we need a relative motion. As MR fluid actually sticks into the workpiece surface there is no relative motion in between this workpiece and this MR fluid because there is a certain layer of this MR fluid actually which sticks to the workpiece surface so that is why it sticks that is why there is a less relative motion is there in between this MR fluid and workpiece so there is a very less improvement in surface finish.

Also you can see from this figure this magnetic contour lines here it is totally uniform but here this magnetic contour lines it is not uniform. It is concentrated towards the magnetic workpiece. So that is why with magnetic workpiece we got very less improvement in surface finish

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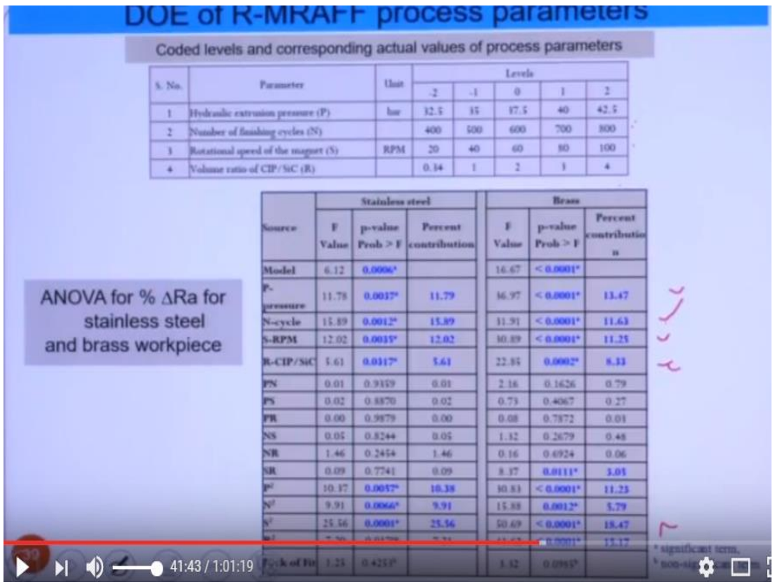

So this is the Anova we have done with 4 parameters, hydraulic extrusion pressure, finishing cycles, rotational speed of the magnet, and volume ratio of CIP and SiC, CIP and silicon carbide abrasive particles. We have considered 0.34 - 4. Hydraulic pressure we have considered 32.5 bar - 42.5 bar, finishing cycles we have considered 400 - 800 and rotational speed of the magnet we have considered 20 - 100.

So by considering all these things we have found that rotational speed of the magnet has highest contribution, finishing cycles also has contribution, and pressure also has highest contribution okay and S square has has also has a contribution 18.47%. So these are the significant parameters, pressure, cycle, and rotational speed of the magnet. Although CIP by SiC ratio of the CIP by SiC also significant but its ratio its contribution is less okay. So that is why it is not that significant a parameter in this case.

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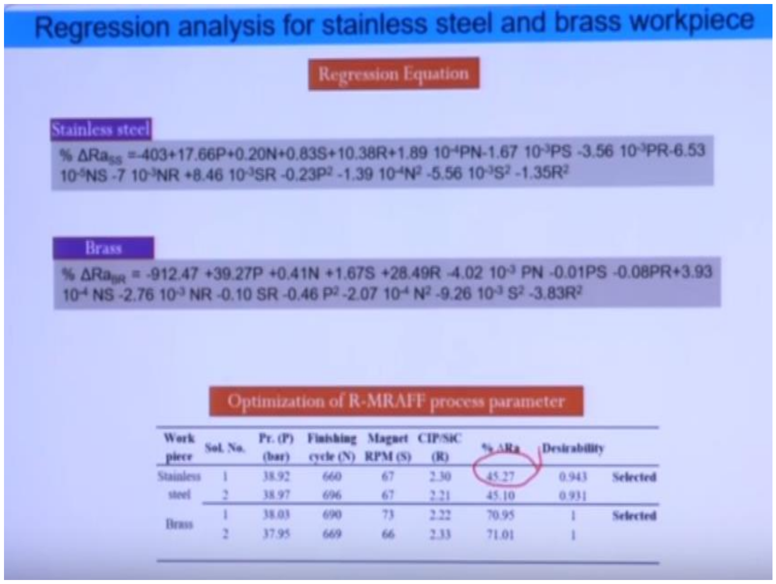

So these are the 2 workpieces we had considered, one is stainless steel another one is the brass. So this is the optimized parameter 39 bar pressure, finishing cycle 660, 67 RPM, and CIP by SiC ratio of R and we got 45.27% improvement in surface finish.

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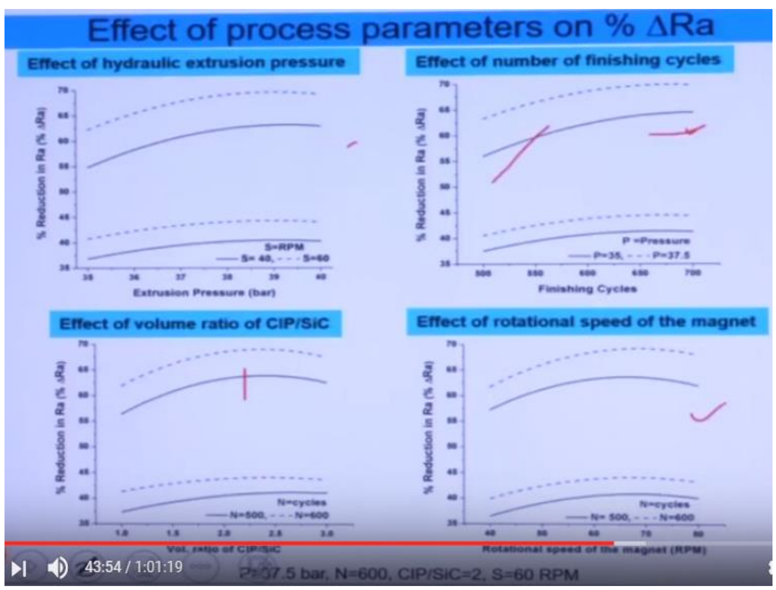

So here also we can see with the increase in pressure surface finish improves, percentage reaction in Ra it is calculated as initial Ra minus final Ra by initial Ra multiplied by 100 it will give the percentage reduction in Ra. With the increase in pressure percentage del Ra increases and it reaches to an optimum value after that actually it stalls. With the finishing cycle also you can see initially there is a high improvement in surface finish but after some time you will see when this finishing cycle increases its actually it is stalls after some time okay.

So the volume ratio of CIP SiC you can see there is a optimum value. Up to this optimum value if we increase the CIP by SiC ratio this surface finish improves after that it reduces because up to certain value your CIP percentage increases. As the CIP percentage increases more strong bond actually will form. Abrasive particles will get more strength to the polishing for polishing but when the CIP percentage increasing more at beyond a certain limit abrasive particles will be less. So in that case less abrasive particle it is because of this less abrasive particle it is very difficult to do the machining polishing. So because without this abrasive particles there will not be any polishing to happen.

So this is the rotational speed of the magnet. Its effect on percentage DLRA it increases with the rotational speed of the magnet, surface finish improves after that due to the shear thinning nature of the speed it stalls reduces after some time.

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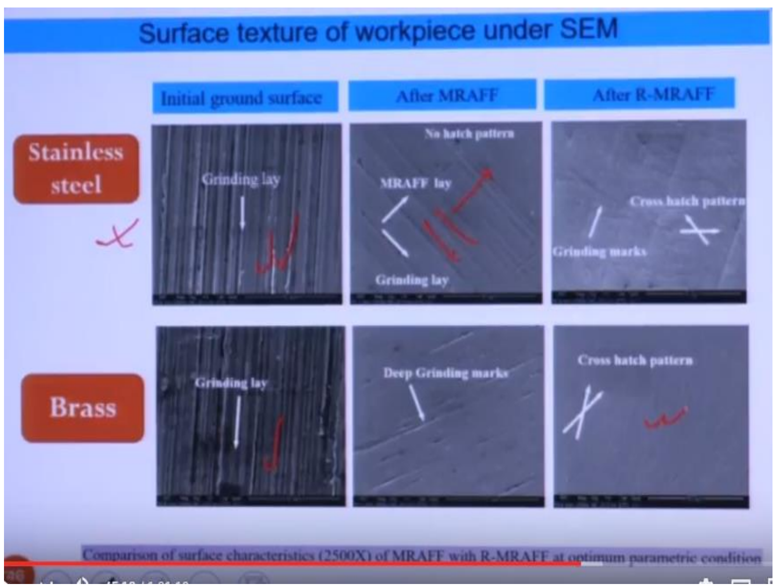

So this is the SEM picture using magnetorheological abrasive flow finishing. So this is the grinding layer direction, grinded workpiece, initial workpieces are grinded. So this is the grinding layer. Here along this direction so you can see here this perpendicular marks are there so which is MRAFF layer which is perpendicular to the grinding layer so after MRAFF you can see lots of peaks and valleys are valleys are available here but you can see R-MRAFF process you can see this valleys are actually separated by long distance. So these valleys are actually separated by long distance okay.

So these kind of cross hatch patterns also you can see it is generated on the workpiece surface. So this is the brass workpiece. This is the grinding layer for this brass workpiece. Here definitely in MRAFF process itself we got a very good surface finish but this kind of scratch marks are there valleys are there but using this R-MRAFF process, rotational MRAFF process you will see this cross hatch patterns and it is all these valleys are completely removed.

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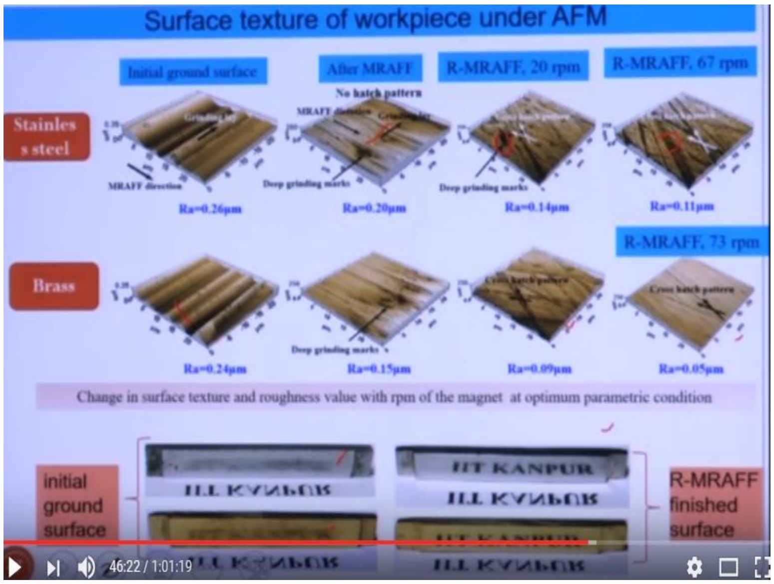

So this is the SEM image for stainless steel. You can see this kind of undulations are there because it is grinding operation okay. So using MRAFF process without rotation these valleys you can see it is clearly visible but using R-MRAFF process you can see these valleys are almost removed although few grinding marks are there which is not removed. By using this MRAFF at optimum rotational speed you will see this all these valleys are totally removed.

Similar case for this brass also you can see this undulations surface undulations are there. So this the grinding marks are there in MRAFF process without rotation. So with rotation you can see we got this 0.09 at 20 RPM and 0.05 50 micron we got at 67 RPM. So these are the initial ground surface for stainless steel and brass. So now it is reflected you can see at the after finishing this IIT Kanpur it is reflected for steel and for brass also.

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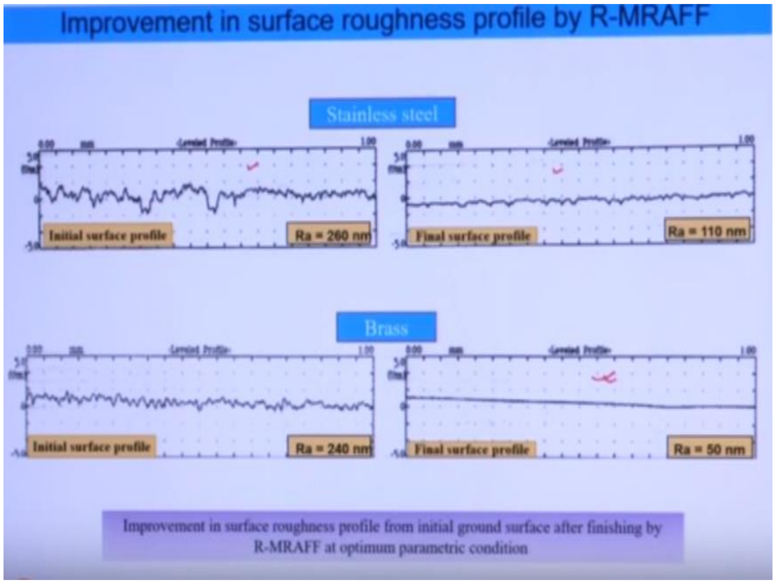

So these are the surface roughness profile, initial surface roughness profile, final surface roughness profile. So this final surface roughness profile you can see it is almost flat in case of MRAFF R-MRAFF process stainless steel for stainless steel. For brass workpiece you can see it has become totally flat. For brass workpiece this surface roughness profile it becomes totally flat. So we got 50 nanometer in case of brass workpiece and 110 nanometer in case of stainless steel workpiece final surface roughness value.

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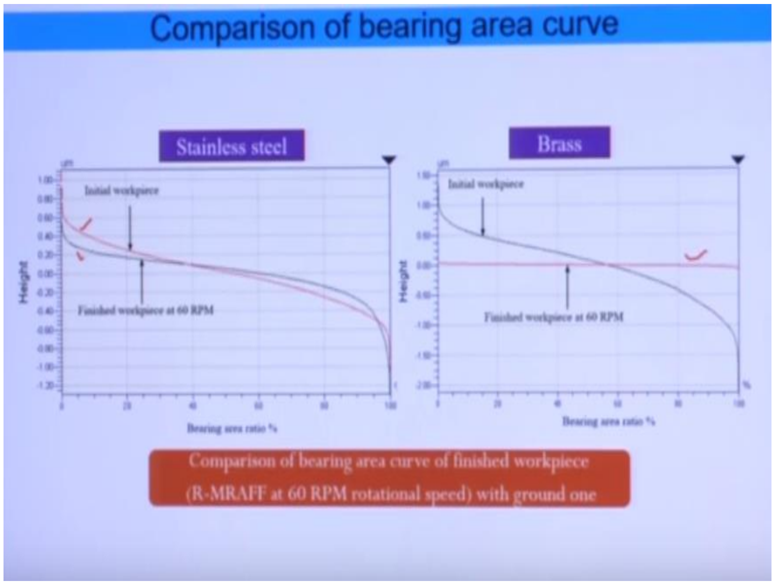

So this is the bearing ratio curve before so this this is the initial bearing ratio, this is the final bearing ratio at 60 RPM we can see so this bearing curve actually flats become flats after polishing but for brass workpiece you can see this bearing curve bearing ratio curve it becomes almost flat totally flat. So higher the flatness of this bearing ratio curve you will get more contact area okay so you can see this bearing area curve also improves using this MRAFF process. So after that we have done the experiments on cylindrical workpiece. So we have used this rotational magnetorheological abrasive flow finishing process for polishing cylindrical internal surface of cylindrical workpieces.

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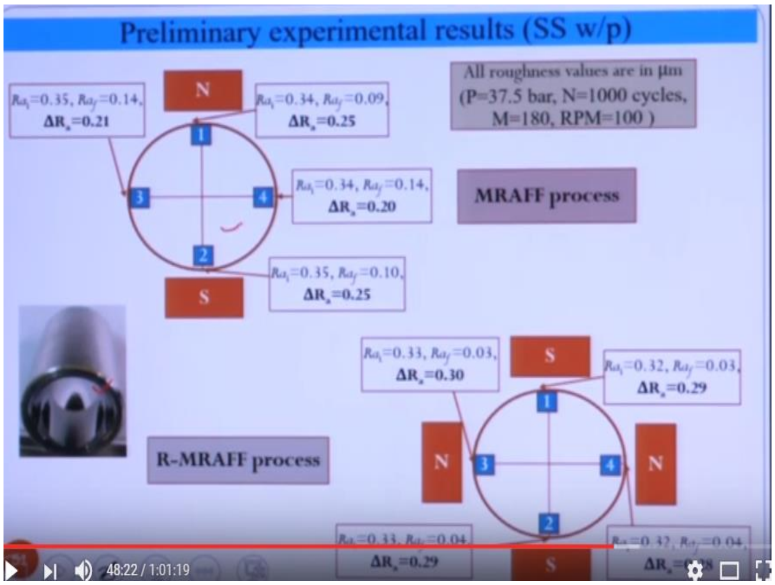

So these kind of cylindrical workpieces we have used. So after MRAFF we have checked the surface roughness at different places and after R-MRAFF we have checked the surface roughness at different places. We have seen that almost uniform polishing we achieved by using this rotational MRAFF process.

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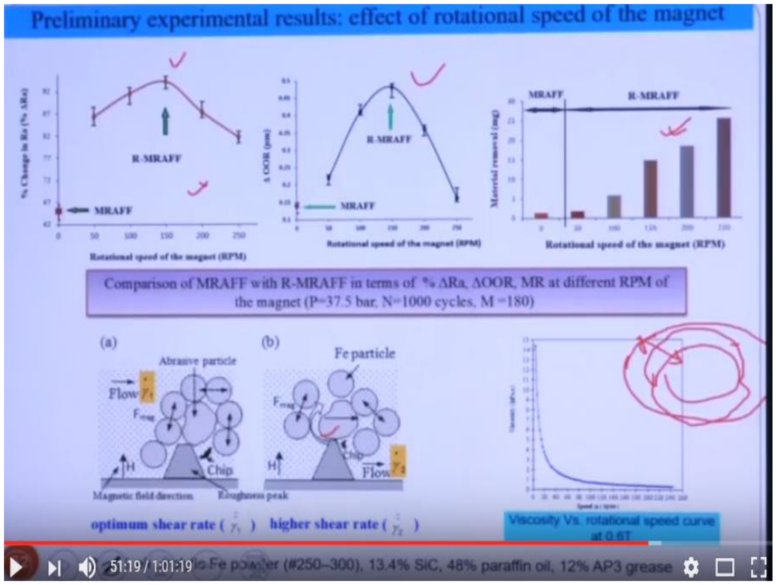

So here also we have checked effect of rotational speed of the magnet on percentage change in Ra. Also we have considered out-of-roundness. So out-of-roundness because our workpiece is cylindrical workpiece as we have considered cylindrical workpiece so in naked eye you will not see any undulations but in out-of-roundness measuring machine if you see so this kind of 2 circles are there sorry this this kind of profiles we will get. So here this is the circumscribed circle and this is the inscribed circle okay. So this distance between the circumscribed circle and inscribed circle will give the out-of-roundness.

So this is the mean surface roughness profile here. So this out-of-roundness is very much important when this 2 when some rotating powers are there okay. It should be perfectly circular. Its cross section should be perfectly circular. So we have seen that R-MRAFF process is capable of improving the out-of-roundness of the cylindrical workpiece. So this is the surface roughness profile. We see that at 150 RPM we got the very good surface roughness and here also 150 RPM we got the very good out-of-roundness.

Also we can see here material removal also improves with the increasing the rotational speed of the magnet. So at optimum shear rate what happens this surface peaks are easily removed and when your shear rate or RPM with the increasing the RPM shear rate of the fluid also increases. When your shear rate of the fluid is beyond the optimum shear rate, at that time because this fluid is actually this chain structure are deformed okay so this chains actually it has less force in between this CIP particles.

So instead of cutting a certain height it will rotate and adjust the height of the peak height or it will adjust, this abrasive particles will adjust the depth of cut and it will reduce the small peaks from the workpiece surface. So with the increasing the rotational speed of the magnet your surface roughness deteriorates beyond the optimum RPM surface roughness deteriorates and also its out-of-roundness also deteriorates although its material removal increases.

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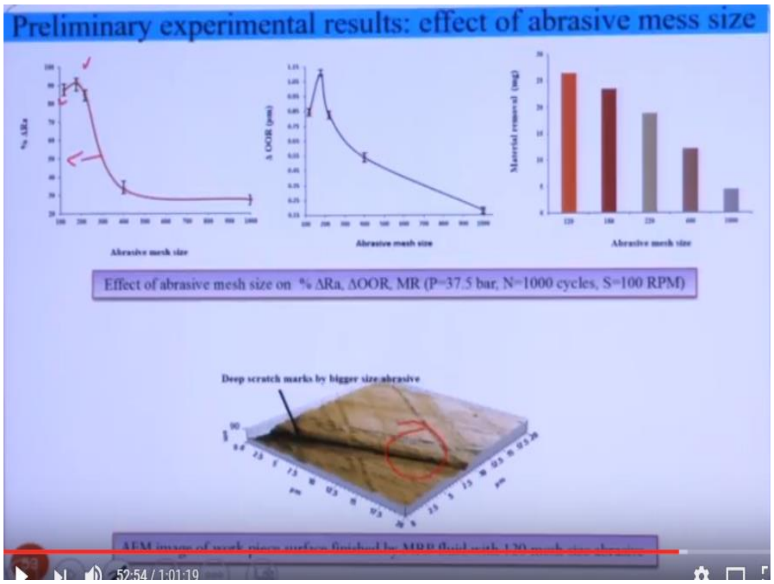

So with mesh size also we have seen we have considered this silicon carbide abrasive particles with the increasing the mesh size means we are reducing the size of the abrasive particles. So suppose from right hand side to left hand side if we consider from smaller size abrasive particles we are considering to the bigger size abrasive particles here. With the bigger size abrasive particles it will remove the surface undulations with the bigger cut with the bigger cut okay. So surface roughness improvement reaches to an optimum value and beyond that actually what happens this CIP particles because this abrasive particle size is too high then the smaller size abrasive particles CIP particles is not able to hold the give the bonding strength to the bigger size abrasive particles.

The normal trend is that trend is that we have to use similar size of abrasive particles and you have to use similar size of abrasive and similar size of CIP particles. Also with the bigger size abrasive particles these kind of scratch marks are also generated. So because of this scratch marks on the already polished surface we got a lesser improvement in surface finish beyond this optimum value optimum size of the abrasive particles .

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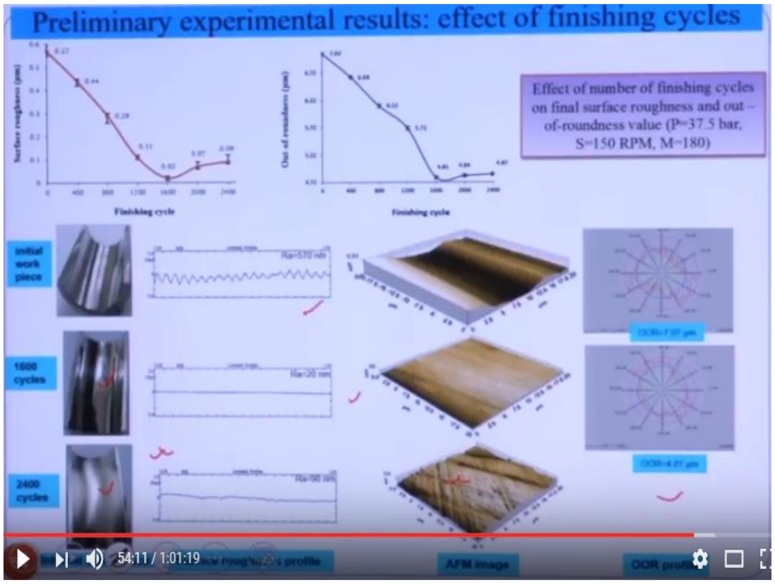

So with finishing cycle we can see surface finish improves. Here at 1600 finishing cycle, very good surface finish is observed but beyond this 2400 finishing cycle we can see this kind of hazy surfaces obtained because at that time this abrasive particles actually give scratch marks on the already polished surface. Here you can see this without finish surface is achieved here because this abrasive particles are actually cutting the giving the scratch marks putting the scratch marks on the already polished surface so beyond this optimum finishing cycle okay so your surface finish deteriorates. So this kind of scratch marks are generated. So surface means out-of-roundness also improves with the finishing cycle. So we can see here from 7.072 we got this 4.81 means out-of-roundness.

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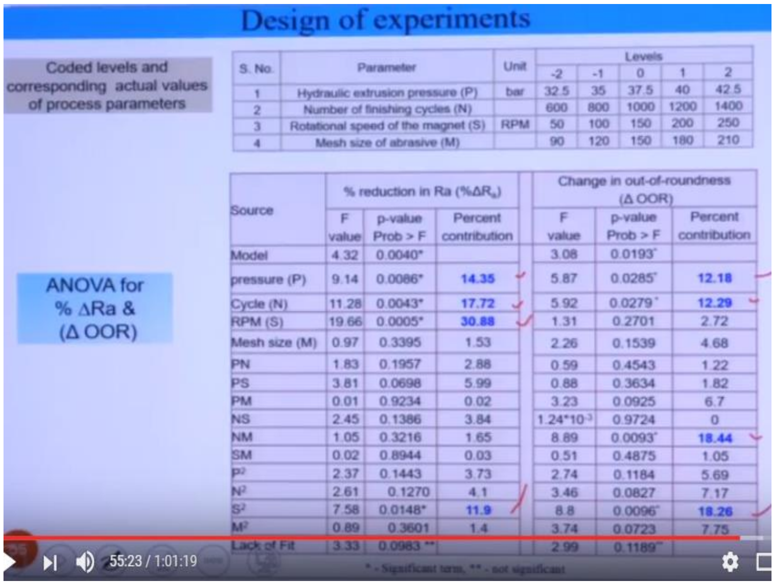

So again we have done the experiments design of experiments using hydraulic extrusion pressure of 32.5 to 42.5 bar, finishing cycle of 600 to 1400, rotational speed of the magnet from 52 to 250, and mesh size of the abrasive is 90 to 210. So here we can see that rotational speed of the magnet has given we got the highest contribution then finishing cycle then finishing pressure. Then again S square also square of this finishing cycle and rotational speed of the magnet also gives higher contribution so it is also very significant parameter. For out-of-roundness also we got this finishing cycle is the important parameter, significant parameter, most significant and then this is the pressure and also some cross parameters are there N into N and S square also there.

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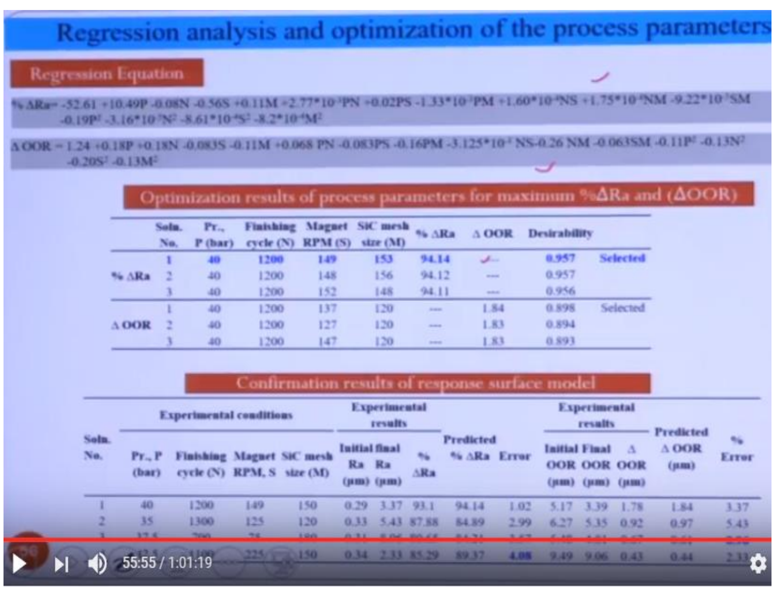

So this is the optimum process parameter 40 bar pressure, finishing cycle 1200, magnet RPM 149, silicon carbide mesh size of 153 we got 94.14% improvement in surface finish. So this is the regression equation for this percentage change in Ra and for change in out-of-roundness this is the regression equation.

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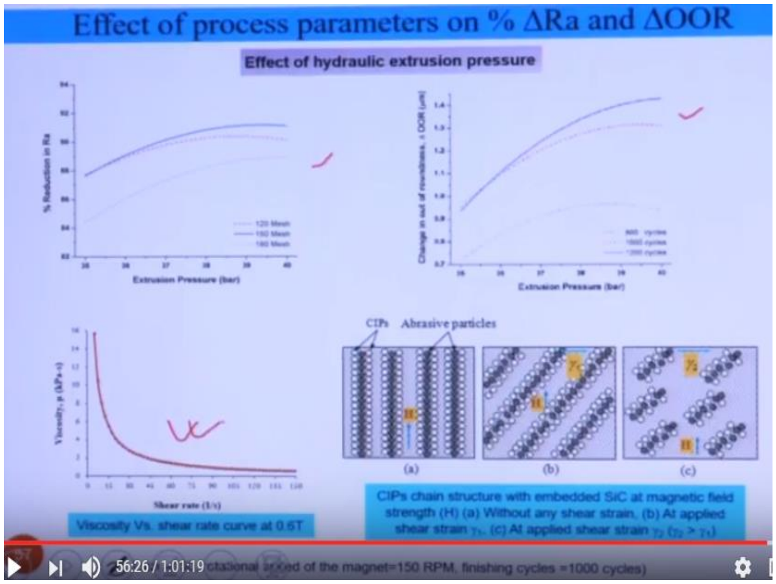

So after that we have done the parametric study with the extrusion pressure you can see percent change in Ra increases after that it stalls. Change in out-of-roundness also with the RPM it increases because of higher centrifugal force, higher tangential cutting force. After that due to the shear thinning nature of this fluid it stalls. So this shear thinning nature it is shown here.

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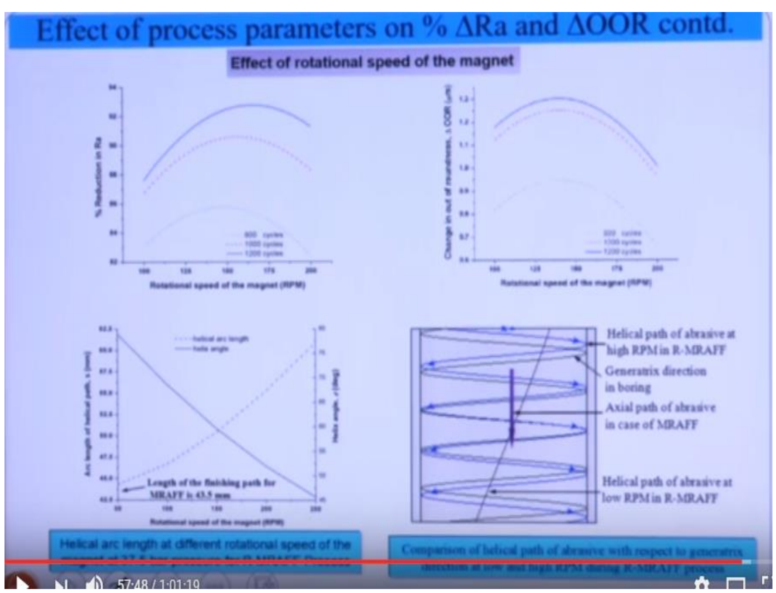

Rotational speed effect of rotational speed on percent change in Ra again you can see when you are increasing the rotational speed of the magnet, after some time it will happens that helical path of the abrasives and generatrix marks okay so whatever this workpieces actually it is made by boring operation okay. This stainless steel workpieces are made by boring operation into the boring operation.

When we are using this when we are increasing the RPM of this magnet, after some time we will see this whatever generatrix marks are there and this helical path of this abrasive particle they take similar path. So instead of cutting it is following the same groups so that is why it is not it is not cutting. But with the increase in the rotational speed of the magnet you can see here your arc length actually increases. So it is taking more path considering it is covering more path on the workpiece surface that is why your surface roughness improves initially but after that because of this it is taking the same path so that is why surface roughness deteriorates.

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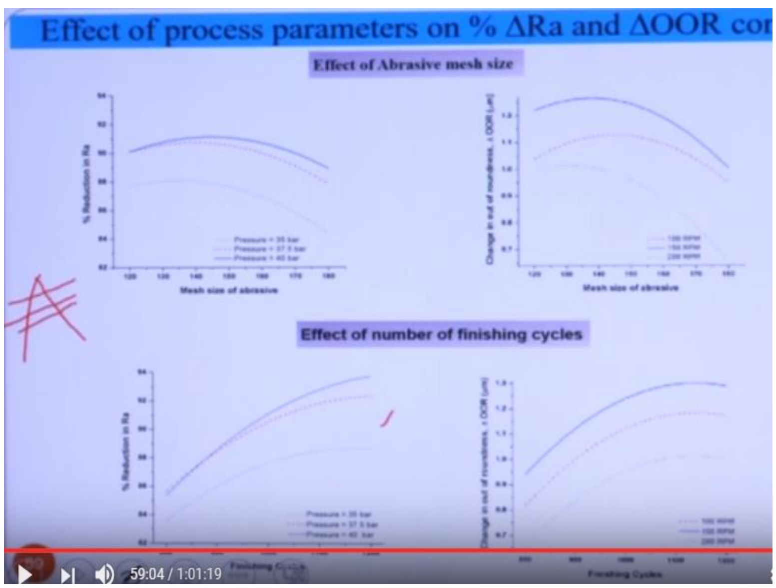

With the mesh size also we can see with the already we had discussed with the increase in the mesh size your smaller size abrasive particles are there so more abrasive particles are taking part into the polishing so that is why surface roughness improves. After that if we increase the mesh size of the abrasive particles more abrasive particles will be there okay so there will be less CIP particles to give the bonding strength to the fluid. So with the increase in the finishing cycle also you can see percent change in Ra increases.

Initially there will be high rate of change in Ra but later it stalls. Initially this (()) (58:36) material actually it is removed. After that proper peaks and valleys are actually available so this abrasive particles takes actually initially this peaks are actually very high so it is very easy to cut but after that this width of this peak actually increases so that is why after some time it is becoming difficult by the abrasive particles to cut the surface peaks.

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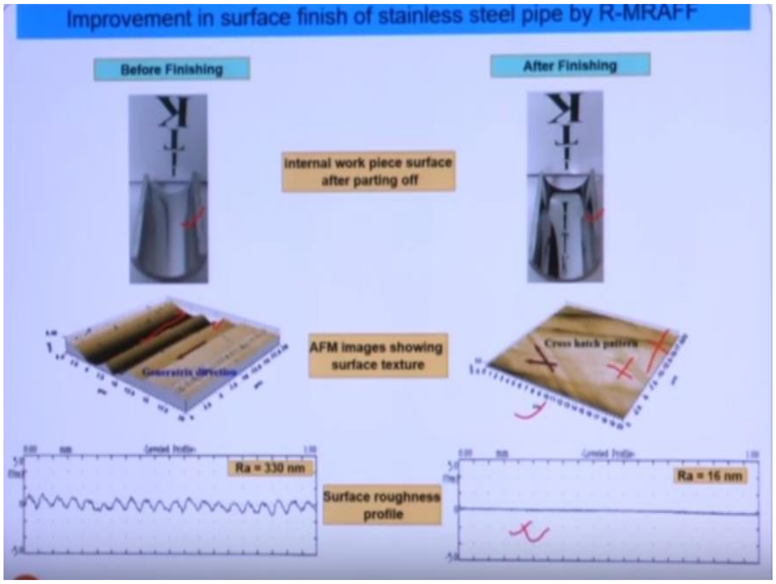

So this is the initial workpiece surface, this is the final workpiece surface you can see after polishing this kind of mirror, mirror finish surface we shall we achieved. So this is the initial workpiece surface. This kind of surface undulations are there so these are the generatrix marks are there and after polishing you can see this kind of cross hatch patterns are actually generated. So this kind of cross hatch patterns are required for actually for this cross hatch patterns are required for in cylinder cylinder boring operation for in piston cylinder that inside cylinder it is actually hone it is honed surface are there. So this kind of cross hatch patterns are generated. It helps in oil retention. So initially this kind of undulations are there because it is boring operation so that is why this kind of generatrix are formed. After that you can see this kind of fair surface flat surface is generated, almost flat surface we achieved, very high surface finish as 16 nanometer.

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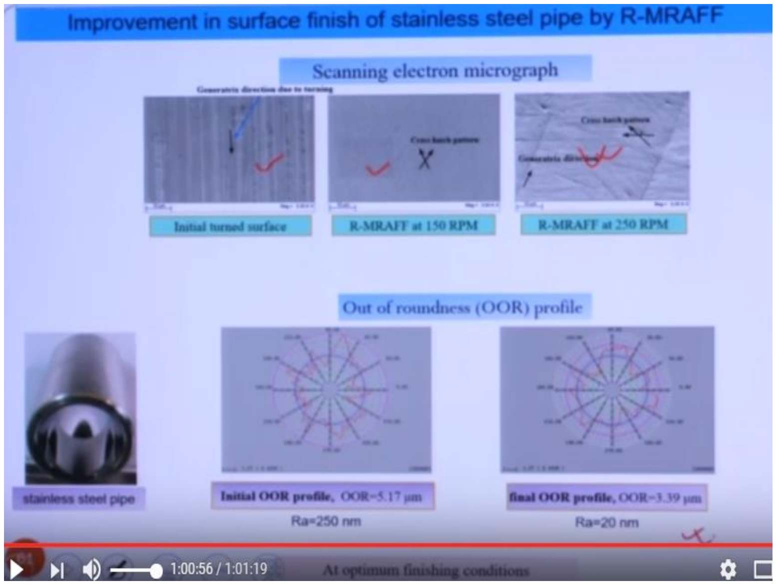

So this is the SEM image, initial workpiece surface R-MRAFF with 150 and rotational MRAFF process at 250 RPM. With optimum RPM we can see very good surface finish is achieved but at high RPM this abrasive particles because of this their random marks the surface finish actually deteriorates. So initial surface means out-of-roundness we achieved we got after boring operation it is 5.17 micron and after polishing we got 3.39 micron final surface finish.