Advanced Machining Processes
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Module - 04
Lecture - 11
Magnetorheological Abrasive Flow Finishing (Part III)

Welcome to the course on advanced machining process. Today we are going to discuss on modeling and simulation of surface generation in magnetorheological abrasive flow finishing process. So this is our experimental setup of magnetorheological abrasive flow finishing process.

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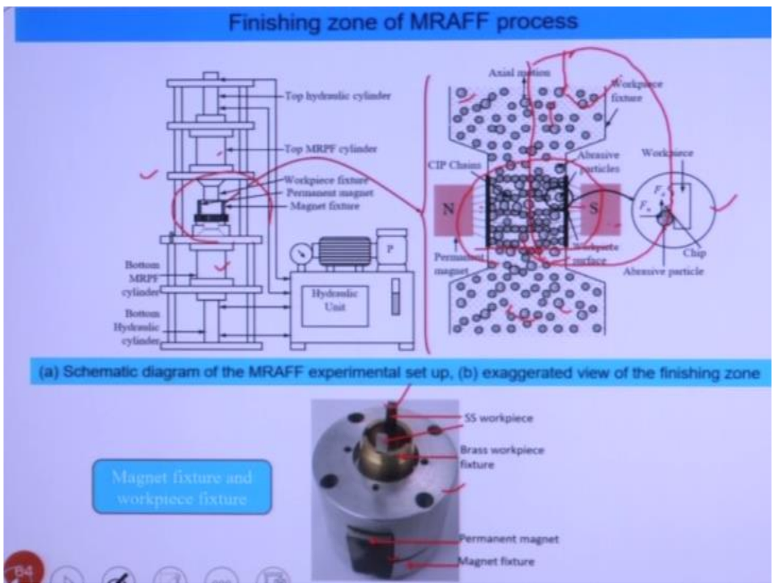

Here, so we can see the setup here is the media cylinder, top media cylinder, this is the bottom media cylinder and this is the finishing zone here. So this finishing zone here it is exaggerated. So finishing zone where actually we keep our workpieces for polishing to take place and on that workpiece on that zone only where you want the polishing we want we need we apply magnetic field there where we need the finishing only.

So you can see here 2 poles of the electromagnet here, north pole and south pole here we kept. So for the current analysis we are not considering any electromagnet so we are considering only permanent magnet so you can see here the fixture, workpiece fixture here. So this is workpiece fixture as well as your magnetic fixture so you can see here this magnets are there at the cylindrical surface at the external surface of the magnet fixture we kept permanent magnets. So these magnets are neodymium, iron, boron. So simply it is called as N.

So we have considered 2 types of magnets, one is N17 and N48, 2 grades of magnets actually we have considered. So this magnets are kept just opposite to each other. So that is why you can see here this is the north pole and this is the south pole. So one thing we want to say here so this is only magnetorheological abrasive flow finishing process and we are not applying any rotational motion of the magnet. So only this magnets are actually fixed here like in magnetorheological abrasive flow finishing, so this magnets are fixed. We are not considering any rotation to the magnets in the current case.

So in this exaggerated view of the workpiece fixture you can see, so this is the extrusion process here. At the top portion there is extrusion process. So here it is connected to the media cylinder and this is the finishing zone at the center, finishing zone where we have applied magnetic field. So this 2 poles are there, north pole and south pole. So you can see the magnetic lines of force here. So this all this carbonyl iron particles are forming chains here you can see.

So these chains actually, these chains are not a continuous chain because we have mixed abrasive particles are there. So these abrasive particles when it comes in between these chain parts, these chains breaks so all these chains are not continuous chain and also this is this simulation we have considered it is in the static case.

So although during finishing MR polishing fluid it is given a reciprocating motion but in the current case we have considered this is a static case where these fluid are fixed here okay so this permanent magnets you can see here at right hand side what are the forces are coming so because of this magnetic magnetic field so magnetic normal force will be there and one axial force is there because of this reciprocating motion or axial motion of the fluid reciprocating motion of the fluid or fluid is flown through the cylindrical fixture with a very high pressure so because of that also magnetic means axial force is there, also one normal force is there, also magnetic force are, force is there due to this applied magnetic field.

So these abrasive particles are held in this zone only in between this carbonyl iron particles. So here in this finishing zone where you are applying magnetic field so we kept our workpieces. So you can see here this at this workpiece fixture you can kept we kept this flat workpieces there at the internal slots of the workpiece so these 2 workpieces are kept just diametrically opposite to each other. So one is in front of this north pole another one is the in front of the south pole. So here this MR fluid in this zone it behaves as a non-Newtonian fluid with the application of magnetic field but where we are not applying any magnetic field there fluid actually means behaves as a Newtonian fluid. So here and here these fluids are actually behaving as a non-Newtonian fluid and one more thing is that with respect to workpiece okay so with respect to this magnet axis, so this axis, you can see this total this top surface top portion of the extrusion means extrusion is similar to the bottom portion is the bottom portion of the extrusion.

So in the first stroke so this piston is moving from top media cylinder to the bottom media cylinder okay so bottom portion of the media cylinder top to the bottom. So this fluid is moving from the top media cylinder to the bottom media cylinder. So extrusion actually in the first cycle extrusion is from the top media cylinder to the bottom media cylinder and in the next cycle actually this extrusion happens on the bottom media cylinder to the top media cylinder. So these 2 process are symmetric with each other. So that is why for the finishing zone we have considered this portion and this portion. So this portion only we have considered for finish means for simulation because these 2 portions are similar to each other.

Also we have considered only one half of the fixture because we have considered for one half of the fixture because we have considered here axisymmetric case okay. So because of this axisymmetric case, we have considered only one half of the fixture here in the current process.

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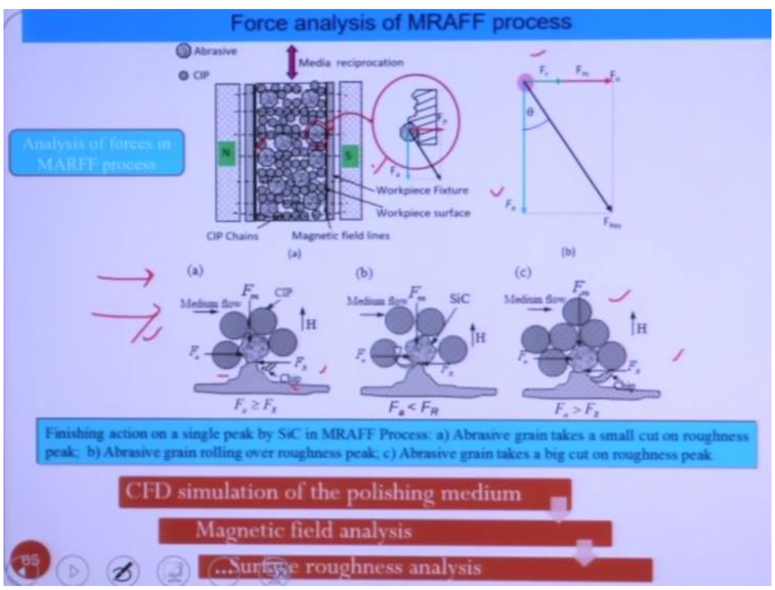

So here you can see how many forces are there on the abrasive particles which are taking part into the surface, taking part in the finishing process. So here this is shown in the finishing zone. This workpiece fixture so you can see at the internal surface of this workpiece fixture 2 workpieces are kept here so this CIP particles are forming chains along the lines of magnetic field. So because of this reciprocating motion of this polishing medium so 2 forces are there, one is the axial force which is axial force and another one is the radial force. So these radial force are perpendicular to the abrasive particles, so this is the radial force here okay so this is the radial force here so which is perpendicular to the abrasive particles okay so this because of this radial force this abrasive particles are intended into the workpiece surface okay.

Now for the cutting to takes place the abrasive particles has to be moved forward. So it gives for moving forward this axial force actually coming into picture so because of this axial force this whatever intended materials are there it is removed from the workpiece surface. So there are because of this reciprocating motion or extrusion of this polishing media inside the workpiece fixture, 2 forces are there, one is the radial force, another one is the axial force.

So because of this radial force indentation occurs and because of this axial force this whatever materials are there it is whatever indented materials by the abrasive particles are there it is removed from the from the workpiece surface, this indented materials are removed from the workpiece surface. Now another force is there, because of this iron particles are attracted toward the poles, toward the north and south poles of the magnets okay, so because of that actually this CIP particles chains are forming this in between these chains abrasive particles are held.

So because of this magnets, magnetic particles are surrounding this abrasive particles so one magnetic force also it is acting on the abrasive particles through CIP particles chains. So this magnetic particles also it is added and normal to the workpiece surface so whatever the total normal force into the workpiece surface is magnetic force and plus axial force that is what magnetic force and radial force. So this is total force that one is the radial force another one is the magnetic force. These 2 forces are helping in indentation into the workpiece surface.

Now axial force actually whatever indented materials are there it is removed from the from the workpiece surface because of this axial force okay. So this resultant of these 2 forces actually do the polishing operation. Okay so now in this picture, in the first picture you can see here this CIP particle chains are actually surrounding the abrasive particles giving the bonding strength to this abrasive particles. When this abrasive particles is moving forward because of this axial motion so because of this axial force actually whatever intended undulations are there it is coming in the form of chains.

So this for indentation to takes place this axial force should be more than the resistance offered by the workpiece material. So this Fa should be greater than this resistance offered by the abrasive, resistance offered by the workpiece material okay. So medium flow is from left to right hand side directions. Now when axial force is greater than radial force so then cutting occurs. In the second case axial force is less than the radial resistance force. So when axial force is less than the radial means resistance force, resistance offered by the workpiece material or FR so in that case what happens this abrasive particles whatever intended into the workpiece surface is not able to remove the surface undulations from the workpiece surface although it is intended.

So in that case this abrasive particles will rotate itself and because of rotation this depth of indentation actually adjusted, it adjusted automatically so after its adjusting its depth of indentation into a lower value or lesser value this at that point actually axial force is greater than resistance force FR okay. So in that case these abrasive particles will remove the small depth of indentation from the workpiece surface.

Now this is the third case here. When axial force again it is greater than greater than resistance force so here whatever intended material is there it will actually removes the surface undulation. In the first case actually it is just equal to resistance force so indentation will start okay. So these are the 3 cases are there where F axial force just equal to the radial force resistance force okay so in that case indentation is ready to start and in the second case axial force is less than radial force resistance force so in that case these abrasive particles will rotate and based on its axial force okay so it will adjust itself and it will cut with a lesser depth of indentation because of its because of its rotation and the third case axial force is very very greater than resistance force in that case whatever indentation is there it will remove the surface undulations accordingly.

So these things are actually simulation of this magnetorheological abrasive flow finishing is required to automate the process. We want to automate the process during machining okay. So what are the forces are there so total force is because of this extrusion pressure axial force and this radial force is there. So this axial force and radial force can be calculated from the computational fluid dynamic simulation. So we shall discuss that thing now. So from the computational fluid dynamic simulation of the polishing medium we can calculate the axial force and radial force.

Now this magnetic force actually can be calculated from magnetic field analysis, this AFM can be calculated from the magnetic field analysis and after that after getting all these forces we can simulate the surface roughness modeling okay so we have to do the surface roughness modeling okay. So after doing the surface roughness modeling whatever surface roughness we get or we achieve so that can be compared with the experimental results. So if it is validated then without doing the experiment original prototype experiment we can automate the process how many what should be the pressure, what should be the magnetic field, how many finishing cycles we need, what we for getting a certain surface finish, final surface finish. So that is the motto for doing the simulation for getting the automation for developing a automation of the system MRAFF process automation of the MRAFF process okay.

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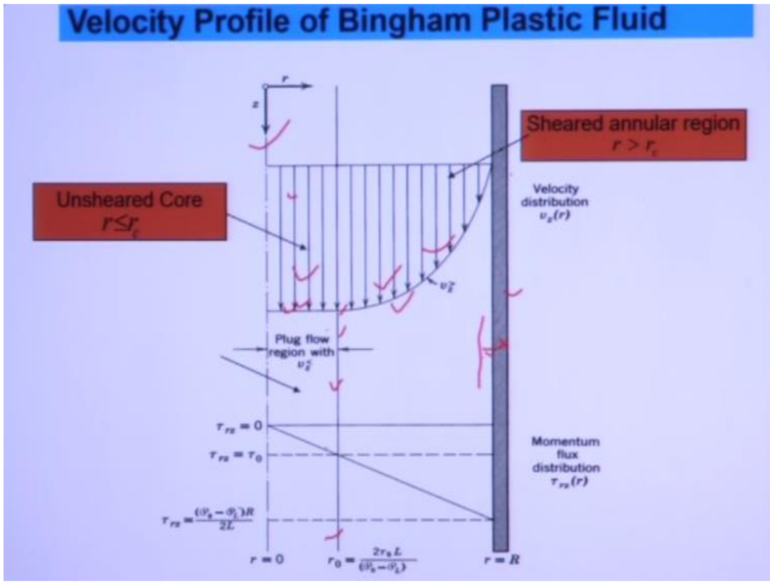

So here you can see the velocity profile in case of Bingham plastic fluid. So Bingham plastic MR magnetorheological polishing fluid can be considered as a Bingham plastic fluid so it can be means it can be considered as a Bingham plastic fluid after application of the magnetic field. So with the application of the magnetic field you can consider this one as the Bingham plastic fluid.

So this is the one-up of the velocity profile for the cylindrical fixture for one-up because we are considering the axisymmetric case so this is the run-up of the cylindrical fixture. So this is the axis of the cylindrical fixture. So this is the wall of the cylindrical fixture. So you can see that velocity profile here at this portion actually velocity profile is constant. So you can get the uniform velocity profile at the center up to this point.

So up to r equal to r 0 you can see here r equal to r 0 this velocity is constant okay. So velocity or unsheared core of r equal to r c, r c here, r equal to r c this velocity is constant. After that this velocity of this MR fluid actually it is sheared here at this zone, here this velocity of this MR fluid is sheared. So where it is not unsheared so MR fluid is not sheared in this zone at the center, so it is not sheared, so this zone actually it is called solid core region or unyielded region, unyielded region or solid core region of the magnetorheological polishing fluid. So here this velocity gradient equal to 0. So there is no change in the velocity profile.

But after that in the in this zone this fluid is sheared. So when radius of the fluid is greater than r c, critical radius, in this zone this velocity of this fluid actually sheared. So velocity of the fluid is sheared, fluid is sheared here. So we can see the velocity gradient and at the wall you can see the stiffest velocity gradient which is observed at the wall of the cylindrical fixture okay.

So MR fluid, to flow this MR fluid your fluid has to be sheared otherwise you cannot flow okay. But one thing is that actually in this unsheared region as the fluid is not sheared there this abrasive particles are held in between the strong magnetic field chains okay and in the sheared zone as the fluid is sheared there all this chain structures are disrupted or broken. So as the chain structures are disrupted or broken so in that case as the chain structures are disrupted or broken so in that case what happens actually whatever this MR fluid actually it is not this CIP particles are not able to hold the abrasive particles that strongly. So that is why for the better polishing we need the means higher radius of this solid core region.

So here this if r c critical radius of this fluid if it is near the wall, so it is near the wall in that case actually most of the fluid will be unsheared or unyielded so abrasive particles will be held with a very strong force and in the this portion will be sheared zone here actually sheared zone is required for the fluid to flow okay. So more unyielded region and less yielded region will give the higher polishing rate okay.

So another thing is that you can see here shear stress is 0 here at the center and shear stress is applied shear stress is maximum at the wall. So as the applied shear stress is maximum at the wall when the fluid is flown through the cylinder okay so fluid is actually broken fluid is fluid is actually sheared along the wall only because shear stress is maximum there okay.

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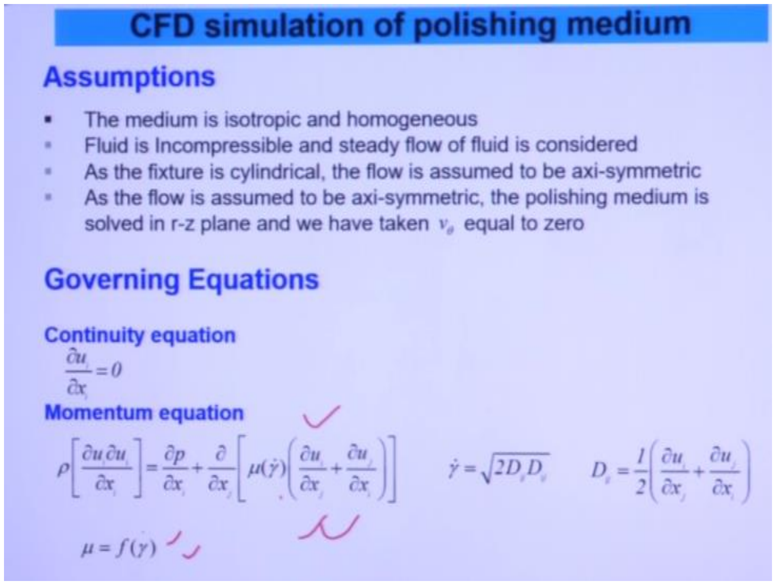

So for this CFD simulation, so we already told CFD simulation is required to calculate the axial force and medial force okay. So for the CFD simulation few things few assumptions are actually required. The medium is isotropic and homogeneous in nature. So this medium whatever we are considering it is isotropic and homogeneous.

Although this abrasive particles, CIP particles are actually homogeneously mixed with the best medium of paraffin oil and grease but for the sake of actually simulation we have considered that total fluid consisting of this abrasive particles as carbonyl iron particles and the base media it consists of a single fluid, single homogeneous fluid okay. So we are not considering any 3 phase flow or 2 phase flow here because solid particles are there liquid also fluid is also there okay so we are not considering all these thing. We are considering MR fluid as a isotropic and homogeneous fluid.

So this fluid is incompressible and steady flow fluid, we are considering the steady flow fluid okay. So as the fixture is cylindrical, fixture is cylindrical so that is why we are considering the axisymmetric case and 2 magnets are actually applied just diametrically opposite to each other. Although this magnetic field is not symmetric but for the sake of actually simplicity we have considered this this case actually as a axisymmetry. We have considered our case as the axisymmetry.

So as the fluid is actually considered as axisymmetry so we are not we are means solving this total problem in r and jet plane, r in the radius direction, jet in the axial direction we are considering the total case as a 2D case, so we are considering the r and jet, r is the radial direction and jet is the axial direction. So we are not considering the soiling motion, soiling motion of this fluid. So fluid is not rotating. So we are not considering this soiling motion of the fluid okay. So we are considering v theta equal to 0 okay.

So this is the governing equations for this MR polishing fluid. This governing equations actually it is solved in fluent, so fluent ansys. So we have solved this total problem in a fluent ansys compiler or solver okay. So continuity equation is del u I by del x i. So and momentum equation also it is written in tensor form. So one thing actually you can see here. Here this if you consider this viscous term here, here viscosity of this MR polishing fluid you can see here this viscosity of this MR polishing fluid is a function of shear rate. So this viscosity is not a constant in case of magnetorheological polishing fluid.

So viscosity is a function of shear rate. Also viscosity is a function of magnetic field and magnetic field viscosity is a function of concentration of CIP okay. So viscosity is not constant in case of magnetorheological polishing fluid. So it is a function of shear rate, it is a function of CIP concentration, it is a function of magnetic field okay. So as the viscosity is a function of shear rate so that is why we cannot put keep our this viscosity outside of this bracket so that is why it is kept inside, viscosity is a function of shear rate and magnetic field.

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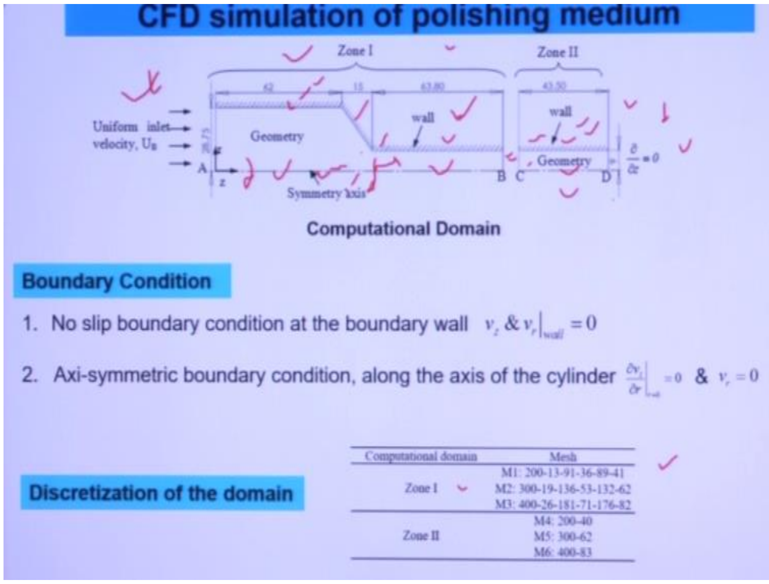

Computational domain	Mesh
Zone I	M1: 200-13-91-36-89-41 M2: 300-19-136-53-132-62 M3: 400-26-181-71-176-82
Zone II	M4: 200-40 M5: 300-62 M6: 400-83

So this is the total domain, computational domain. So here we can see here again we can show so this is the our domain so we are considering only this zone, so this zone we are considering only okay. So here this is homogeneous means Newtonian fluid, here under magnetic field. This is not

Newtonian fluid okay. So considering this one here up to this point from here to here this point we are not applying any magnetic field and from here to here we are applying magnetic field. So there are 2 zones of this flowing fluid. So first one is the zone I where we are not applying any magnetic field and in zone II actually at the internal surface of this workpiece fixture we kept our workpiece there and that is why we have to apply magnetic field here. So here in zone I this MR fluid has a Newtonian fluid and in zone II actually this MR fluid has the non-Newtonian Bingham plastic fluid okay.

So this particular dimensions of this fluid actually it is given here. So from here to here it is 62 mm then there is an extrusion of process is there and from here to here it is 63.8 mm. So here this extrusion occurs here. So after extrusion from here it is outlet and from here actually it is going to the zone II where in zone II we are we have applied this magnetic field.

So here in zone II actually MR fluid behave as a non-Newtonian fluid okay. So what are the boundary conditions are there. So we have considered we have actually we have solved this total thing in a ansys fluent okay. So in ansys fluent we have we have solved this 2 total thing. First this zone I actually solved. So in this zone I, first this zone I is solved. So in this zone I MR fluid actually it is a Newtonian model. So here it is it applies means we have considered this is a Newtonian fluid in zone I okay.

So fluid is actually entering into the polishing medium or entering into the finishing zone with a uniform velocity. This is the uniform inlet velocity. This velocity actually considered with the assumption that this whatever piston velocity is there so this piston velocity actually we are piston velocity in the medium cylinder it is it is coming with a certain velocity okay. So although this velocity is a sinusoidal it will be a sinusoidal it is not constant but we have considered as a average value of this piston velocity as the inlet velocity of the fluid into the zone I okay.

So this average velocity of this average velocity of this fluid at the inlet of this zone I is considered as the inlet velocity to the zone I. So average velocity of this piston at this is considered as the inlet velocity of this fluid at in zone I. So that is U B equal to constant here. So after it is entering into this into this zone, in zone I you can see this is the wall boundary here. So at this boundary at the wall actually we have considered no slip boundary condition here.

So here also we have considered no slip boundary condition and at the along the along this axis so this is the axis here. So along this axis we have considered axisymmetric boundary condition and at the outlet actually we have considered this fully developed velocity profile, fully developed flow condition or fully developed velocity profile there at the outlet we have means it is achieved, we have assumed there fully developed flow condition velocity profile is considered at the outlet of this zone I.

So because of we are considering this fluid in the r and jet plane so v r both v r radial force and this axial force both v r and v z perpendicular to this wall equal to 0, both v r and v z perpendicular to this wall is 0 okay. So and at the axis actually we have considered axisymmetric boundary condition, so this axisymmetric boundary condition can be written as del v z velocity of z direction velocity with respect to r equal to 0.

So gradient of velocity with respect to radial direction is 0. So or del v z by del r, at r equal to 0 at the along the axis equal to 0 and v r there is no cross flow of this fluid along this axis. So v r also 0 along the axis of the along the axis of this zone 1 okay. So whatever this outlet velocity calculated from this zone I okay so that is considered as the inlet to the zone II okay and also at this wall along this wall we have considered no slip boundary condition in zone II okay. So at in zone II we have considered at this wall no slip boundary condition again.

So v r and v z radial velocity and axial velocity both are 0 perpendicular to this wall and again along this axis we have considered del v z by del r axisymmetric boundary condition and at this outlet actually we have considered again fully developed flow condition or del v z del z equal to 0 along the outlet and at the inlet actually we have considered velocity which is coming from the from the outlet of this zone I with whatever velocity is there it is considered as the inlet to the zone II okay.

So for this computational domain we have considered for zone I, we have considered this it is M1, different mesh we have considered for mesh independent test. So this is M1, M2, and M3. With this 200 in this long distance it is 200. In other cases this is 13, then this is 19. So we have considered like this. So in zone I we have considered like this and for this zone II okay for this zone II this we have considered 200 elements along this x means along this jet direction and along this radial direction we have considered 40 elements okay.

So these are the elements here for mesh independent test for both zone I and zone II and we have found that in zone I actually there is no change in velocity profile for this 200 to 300 okay. So very small change in velocity profile is observed and for this zone II also we have considered from 200 mesh size to 300 mesh size along this x direction so very few very few change in actually velocity profile is observed. So from this from this so discretization this first mesh 1 M1 is considered for this zone I and M4 is considered for this zone II from grid independent test.

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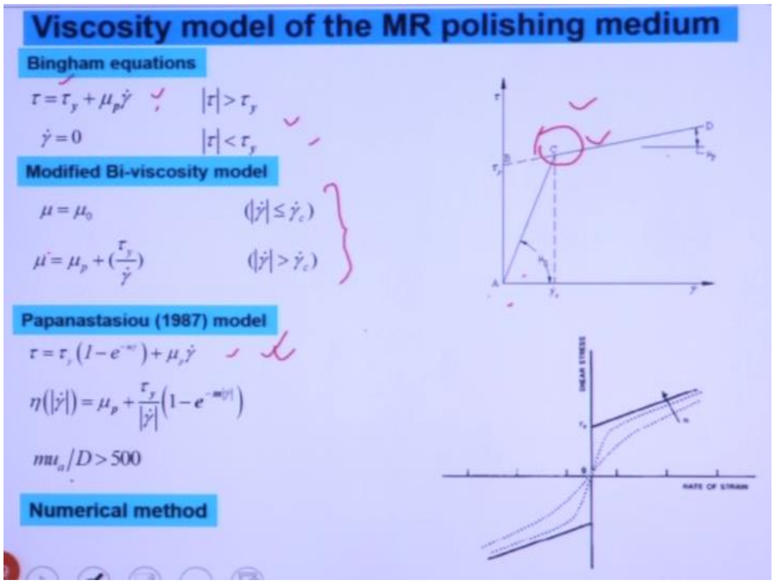

So after that we have to consider this viscosity model. As we have told that MR fluid actually it is a non-Newtonian fluid with the application of magnetic field so it can be considered as the Bingham plastic fluid with the application of magnetic field. So this is the equation of a Bingham plastic fluid. When applied shear stress is greater than yield stress of this fluid then shear stress equal to yield stress tau y plus mu p is the plastic viscosity into gamma dot is the shear rate okay. So when applied shear stress is greater than yield stress of this fluid so this is the equation for this shear stress and when applied shear stress is less than yield stress of this fluid then fluid does not flow okay. So in that case shear rate equal to 0 fluid does not flow so shear rate equal to 0 in the second case when shear stress, applied shear stress less than yield stress of this fluid. So this Bingham plastic equation can be modeled here.

So this is the this is the Bingham plastic equation for this for this case this is the A B C D so this is the line. So this AB equal to tau y. When applied shear stress is greater than this tau y then only this fluid will flow okay. So this is the after flowing when the fluid flows then it takes the path from takes the path BCD okay. So this slope of this line BCD will give the plastic viscosity mu p. Now this Bingham plastic model cannot be implied cannot be we cannot use this one because suddenly at this point at gamma dot equal to 0 here suddenly at this point at the center actually it drops from yield stress of tau y to suddenly it becomes to 0.

So there is a discontinuity at this point B. So that is why people have actually consider modified Bi-viscosity model, Bi-viscosity model so where actually this flow path of this MR fluid Bingham plastic fluid is considered ACD. It is not ABCD. So this is the ACD. This is the flow path for this modified Bi-viscosity model. So in this case initially there is a very high viscosity is there. So from A to C there is a very high viscosity is there. So mu equal to mu 0.

We can consider mu mu equal to 1000 into mu 0. So very high viscosity is considered initially very high viscosity mu 0 equal to 1000 or mu p. Mu p is the plastic viscosity. So you can consider this mu 0 initial viscosity very high viscosity equal to 1000 equal to mu p you can consider okay.

So after that when it crosses this C point then it takes the viscosity as mu p l or plastic viscosity is considered. So this is the Bi-viscosity model. In this Bi-viscosity model when gamma dot is less than equal to gamma dot C critical shear rate so when shear rate is less than the critical shear rate so in that case viscosity is very high mu 0, mu equal to mu 0 and when shear rate is greater than critical shear rate so in that case we can consider this viscosity as mu equal to mu p plastic viscosity plus tau y by gamma dot.

So this is the viscosity when applied shear rate is greater than critical shear rate okay. So after it gets it matches the critical shear rate then it takes the path of CD okay. So this is the Bi-viscosity model. So here also there is a discontinuity at this point C because beyond this value this takes the viscosity as mu p plastic viscosity but before that means when it passes the point C then in that case viscosity is equal to mu p plus tau y by gamma dot. It is a function of shear rate but when it at the left hand side when it does not reach up to the C point in that case high viscosity of this fluid is considered.

So at this C point actually it is a point of discontinuity in case of modified Bi-viscosity model. So that is why people have actually developed so many models among them. So this is the Papanastasiou. He developed this model tau equal to tau y 1 minus e to the power m into gamma dot plus mu p into gamma dot. So this is the equation he developed in 1987. So this same equation one equation can be used actually to can be represented as the 2 equations in case of modified Bi-viscosity model. So this one equation can be considered as the 2 equation. It can take care of the 2 equations in for 2 equations for modified Bi-viscosity model.

So one equation tau equal to tau y 1 minus e to the power of minus m into gamma dot plus mu p into gamma dot. So this is the equation for Papanastasiou model which means it can be considered as the it considers both the cases of modified Bi-viscosity model okay. So in this case this viscosity is a function of shear rate and equal to mu p plus tau y by gamma dot 1 minus e to the power m into gamma dot okay. So if we considered very high value of m so in that case this Papanastasiou model it actually takes the shape of the Bingham plastic model okay.

So if we considered very high value of this m for high value of m this Papanastasiou model actually it considers it takes the shape of the it takes the shape of the Bingham plastic model okay. Viscosity in that case Papanastasiou model equal to mu p plus tau y by gamma dot 1 minus e to the power m into gamma dot okay.

So that this value of u a this axial velocity should be like that m u a by D should be greater than 500. So these are the this is the model Papanastasiou model. So this model actually it is utilised in fluid. So we have retained a user defined function for this Papanastasiou model for viscosity or for viscosity model we have developed we have used this Papanastasiou model okay for calculating the viscosity okay.

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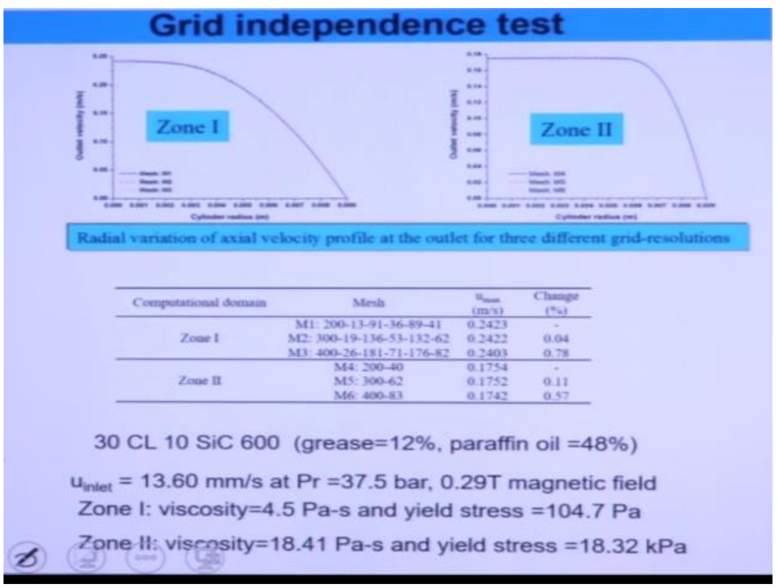

So now we need to do the grid independent test. So you can see this zone I and this is the zone II. This velocity profile at for different 3 different grids okay so this grids for zone I you can see here. So you can see that this velocity there is no change in the velocity profile for this zone I so this maximum velocity at this point for this zone I you can see from M equal to 200 M1 equal to 200 along this length direction then second one is the M1 equal to 300 and third direction M1 equal to 400. So in between this 200 and 300 mesh along this x direction you can see there is only 0.04% change in velocity profile and in zone II also we can see if you plot for 200 for 300 and for 800, 400 you can see so from this 200 to 300 there is very fine change in velocity profile can be observed okay.

So we can consider this 200 by 40 this 200 by 40 this one as the we can consider this 200 by 40 this mesh actually it is considered for this optimized mesh for zone II and for zone I this 200-13-91-36-89 and along this jet direction it is 41 is considered as the optimum mesh size for zone I. So for grid independence test we have considered 30% by volume CL grade abrasive part CIP particles carbonyl iron particles and then 10% by volume silicon carbide abrasive particles with 600 mesh size as the polishing media and grease we have considered this 12% grease and paraffin oil as 48%.

All these values are actually considered from the optimum polishing fluid selection which is discussed earlier where we have studied the rheological property of this polishing media. So this inlet velocity to this media average inlet velocity of this polishing media is considered 13.60 mm/s. So it depends on the pressure. So at 37.5 bar pressure this inlet velocity is 13.60 mm/s at 0.29 tesla magnetic field because in that case we have considered N17 grade of we have considered N17 grade of iron particles. So in zone I this viscosity of this polishing media is considered 4.5 Pa-s and yield stress of this fluid is considered as 104.7 Pa okay. So this in zone I although we are not applying any magnetic field but while doing this rheological characterization we have seen that very less amount of viscosity and yield stress is actually observed.

So you can see here this viscosity is 4.5 Pa-s although in zone II at with at 0.29 tesla magnetic field this viscosity is 18.41 Pa-s okay. So now yield stress also we can see here in case of zone I this yield stress is 104.7 Pa but in in the polishing zone where we are we have applied magnetic field there it is 18.32 kPa. So it is very high. So in zone I it is very less, in zone II it is very high. So that is why a little bit of this viscosity and yield stress is observed although its value is less but for but for getting accurate results we have considered this one into our simulation okay.

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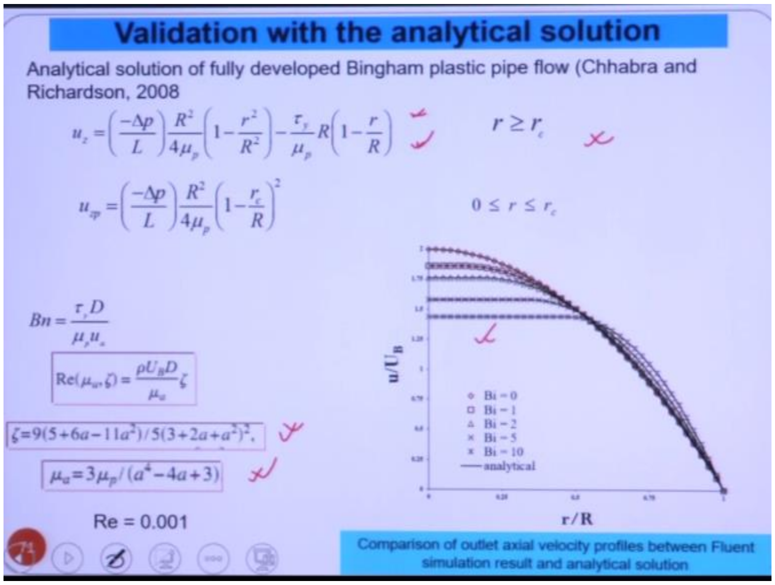

Now we have to do the validation of our model okay, validation of our model fluent model okay, fluent results with the with some analytical results. So there are some analytical solution available for fully developed Bingham plastic pipe flow so this one is taken from Chhabra and Richardson in 2008, their published book from their published book. So here this velocity along this jet direction can be calculated as minus del p by L, del p is the pressure gradient, L is the length of this length of this work length of this actually pipe where you are applying magnetic field and R is the capital R is the radius of this cylinder okay. Small r is the radius at any point okay, tau y is the yield stress, mu p is the plastic viscosity okay.

So this equation will give the velocity analytical velocity profile at any cross section, at any radius or at any length along any length of this workpiece or at any length of this compressional domain okay and then so this r actually this r greater than r c critical radius r greater than equal to critical radius means this one first one is the in the shear zone and r greater than 0 less than equal to r c so when r is less than critical radius of this cylindrical fixture okay so in that case this velocity profile is like this minus del p by l capital R square by 4 mu p 1 minus r c is the critical radius r c by r, r is the total radius of this fixture.

So this one more item is there number is there that is called Bingham number so Bingham number it is defined as tau y by tau y into d into by divided by mu p into mu a. So here this (()) (42:31) number can be written as rho u b, u is the inlet velocity d is the diameter and mu a divided by mu a into zeta, zeta can be calculated form this equation and mu also can be calculated from this equation. So by plotting all this things at different Bingham number and in every case actually we have we have done this analytical solution, we have calculated analytical solution from Bingham number 0 to here at the top Bingham number 0 to Bingham number 10 we have plotted here okay. So at Bingham number 0 means it is like a Newtonian fluid and when you are increasing this Bingham number from 0 to 10 so it becomes as a non-Newtonian fluid okay with higher viscosity and yield stress. So our model actually matches with the analytical solution okay. So we can we can tell that our model is validated now.

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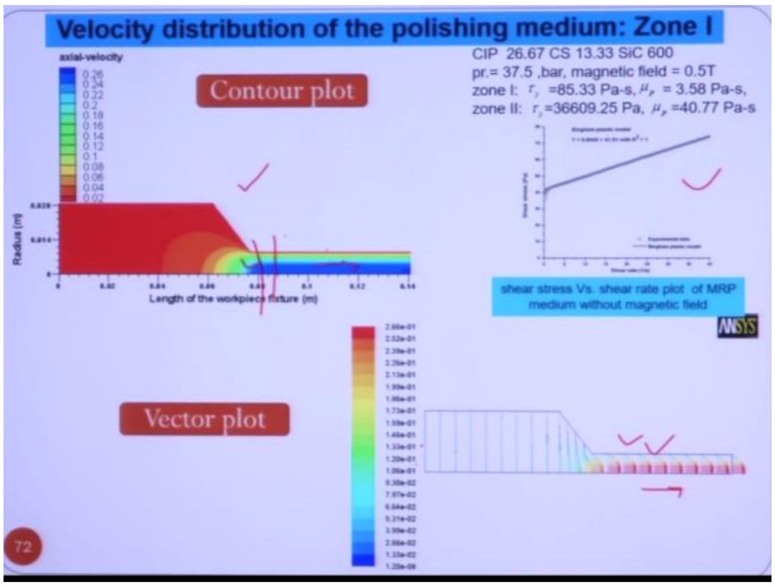

Now we have to do the velocity distribution of the polishing media in zone I. In zone I after doing this fluent simulation okay before that actually we want to tell something what is the numerical method we have used. So we have used actually semi implicit method for pressure linked equation proposed by Patankar. So that method actually is used for discretization okay for discretization of continuity equation and momentum equation this Patankar's semi implicit method for pressure linked equation simple method is used okay.

And now for this viscous term actually we have used central difference method and for this convective term we have used second-order upwind method for this convective term. So this total things actually total thing actually it is run using ansys fluent okay. So it is run using ansys fluent. Now you can see from this contour plot in the unfinished zone or sheared zone you can see without application magnetic field okay so velocity distribution without application of the magnetic field you can see here okay.

So at the inlet actually we have considered the uniform velocity profile. So after so that is why here in this zone almost similar velocity is observed okay. So now we can see after extrusion after extrusion you can see here okay so this velocity gradient changes. So velocity at the center is actually minimum and velocity at the wall workpiece fixture wall at this fixture wall actually velocity is gradient actually very high and at the wall actually velocity again it is 0.

So at the wall velocity, velocity gradient is very high and at the center you can see here this velocity almost same. So this means that this velocity means this MR fluid actually after extrusion actually it is it comes to a fully developed flow condition is achieved after crossing this after crossing this fluid from this extrusion zone okay. So here you can see here in this zone itself this in this zone itself your this MR fluid actually it develops fully developed flow condition. Here this is the vector plot you can see here. At this vector plot you can see this at this zone you can see this is the fully developed flow condition is achieved.

So here this velocity is very less here and here velocity profile actually changes here and we can see higher velocity at the wall and lesser velocity at the along the cylindrical cylinder center. So this is the viscosity model we have considered. So tau y yield stress of this fluid in zone I is 85.33 Pa-s and plastic velocity is 3.4 Pa-s okay. So in zone II it will be Pa so in zone II this tau y is 37 kilopascal kPa and plastic viscosity is 30.77 Pa-s.

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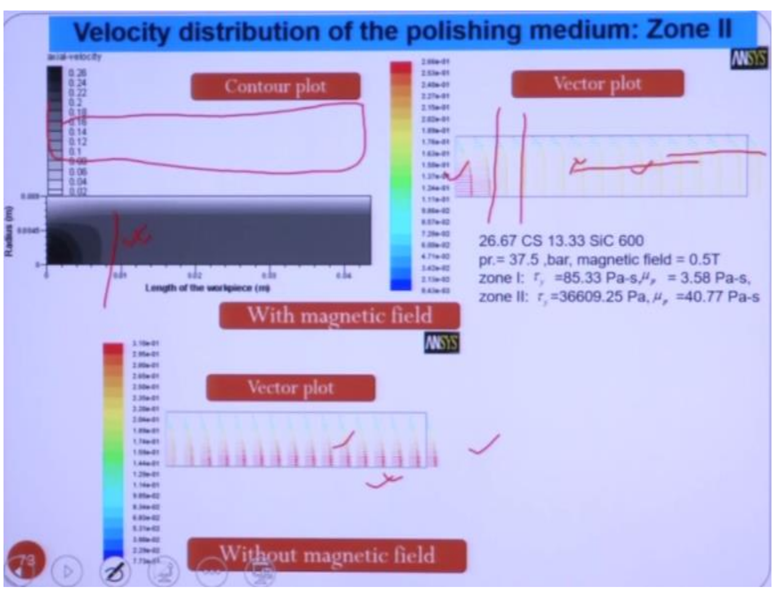

So after doing the velocity profile at the finish means at this without in the zone where we are not applying magnetic field we have to go for velocity profile we have to go for velocity profile for the finishing zone, for the finishing zone. So in this finishing zone there is no extrusion. So here we have applied this magnet. So this magnets is applied in this zone in the finishing zone. So you can see here that so here in the finishing zone so after entering the fluid in the finishing zone in between 0 to 0.01 so near to 0.01 meter you can see this fluid is actually fully developed flow condition is achieved.

So fluid becomes fully developed when it reaches up to 0.01 meter along the length of the workpiece fixture where you are we have we have applied this magnetic field okay. So this is the vector plot of this fluid which is obtained from ansys okay. So in this vector plot you can see here this is the inlet velocity we have given. So this inlet velocity is taken from the outlet of the from the outlet velocity of the zone I.

So that outlet velocity is taken as the input in zone II. Here you can see that here we can see that this velocity gradient actually it is constant up to this point after that this velocity gradient actually changes okay. So fully developed flow condition you can see here, here itself this fully developed flow condition can be achieved.

So without any magnetic field so this is with the application of magnetic field at 0.5 tesla magnetic field so without application of magnetic field here you can see this velocity profiles are parabolic in nature okay but with the application of magnetic field this velocity profiles actually uniform at the same time where this core uniform at the same time so where core material is there and solid core region is there and at the at the wall actually this MR fluid actually it is sheared. So without application of magnetic field there is no solid core region in case of MR fluid okay. So without application of magnetic field so as the fluids are not magnetized so we will not get sufficient forces to control the abrasive particles on to the workpiece surface.

So after doing this one this computational fluid dynamic simulation of MR polishing fluid both in zone I and zone II we can calculate what are the axial force and what is the radial force. So obviously we can get this shear stress and radial stress from this simulation. If we know the shear stress and radial stress so we can calculate how much force is coming to a individual abrasive particles if we have a abrasive particles they are having a certain structure. If the abrasive particles are considered under certain structure then only you can calculate how much force is coming on individual abrasive particles.

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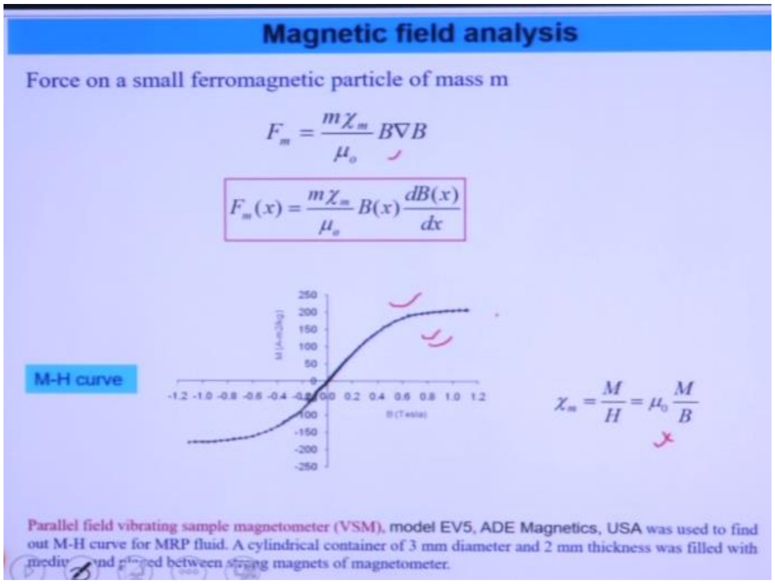

So force on a small ferromagnetic particle of mass m can be calculated, force on a small ferromagnetic particle of mass m can be calculated as F m equal to m into chi m B del B divided by mu 0. So m is the mass of this abrasive particles chi m is the susceptibility of this sorry m is the mass of this CIP particles carbonyl iron particles. So after calculating the forces axial and radial forces from computational fluid dynamics simulation we are going to calculate the magnetic forces on the abrasive particles through surrounding CIP particles okay so using magnetic field analysis.

So what are the force acting on a carbonyl iron particles or ferromagnetic particle in a magnetic field. So this is the equation F m equal to m chi B into gradient B divided by mu 0 will give the force acting on single ferromagnetic particle under magnetic field. So m is the mass of the ferromagnetic particle, chi m is the susceptibility of this ferromagnetic particle and then B is the magnetic field intensity and grad B is the gradient of the magnetic field intensity divided by mu 0, mu 0 here actually permeability in free space okay.

So this equation can be written in terms of function x at a distance at a distance x from the where from the magnet so we have we have considered the distance from the magnet okay. So this F m x equal to m into chi m divided by mu 0 B into x magnetic field intensity as a function of x and dB dx as a function of x okay. So for here mass of individual abrasive particles is known, susceptibility of the magnetic particle can be calculated from can be calculated from the parallel field vibrating sample magnetometer VSM model 5 ADE Magnetics okay USA, so it is used for to find out the M-H curve okay so it is used to find out the M-H curve for MR magnetorheological polishing fluid. A cylindrical container of 3 millimeter diameter and 2 millimeter thickness was filled with the medium and placed in between the magnets of magnetometer okay. So from there so if it is kept inside a magnetic field okay so we can calculate this magnetic susceptibility from there itself okay. So this is the image curve here.

So from this image curve we can calculate the magnetic susceptibility at any distance okay as a function of x we can calculate and also from this curve we can calculate what is the B magnetic field intensity as a function of x we can calculate and if we know this B so we can calculate its gradient dB dx as a function of x okay. So chi m can be calculated as M by H, M is the magnetization, H is the applied magnetic field equal to mu 0 and into M by B okay.

So B equal to mu 0 into H. So H can be replaced by mu 0 by B, B by mu 0 okay H can be replaced as B by mu 0 here okay. So from this equation from here from this image curve which is obtained from the vibrating sample magnetometer VSM we can calculate B x, dB dx, and susceptibility and M is already known and mu 0 is a constant permeability in free space.

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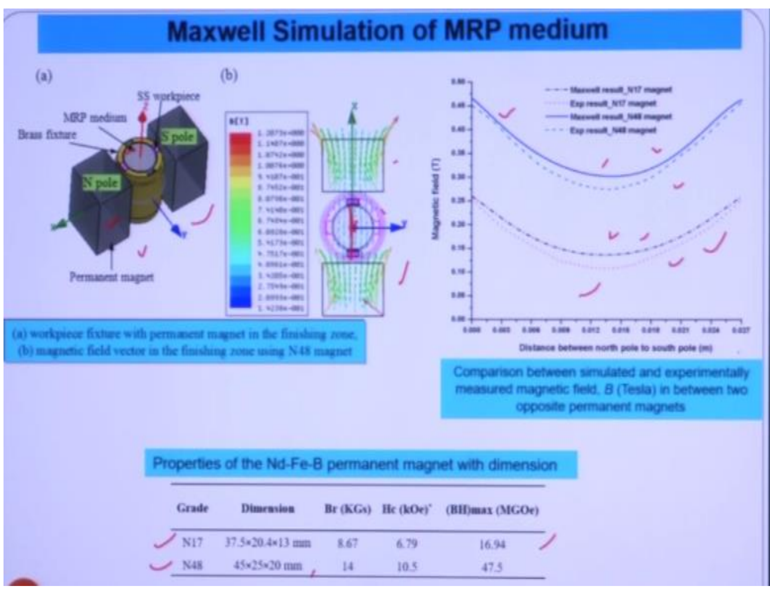

So now we have to calculate the B x what is the value of B, what is the value of B so with as a function of x. So we are we have applied these 2 magnets 2 parallel magnets here north pole and south pole of this magnets are there. Here this is the workpiece fixture, 2 flat workpiece just here and here 2 flat workpiece are used, stainless steel workpiece are kept and this fixture actually it is filled up with magnetorheological polishing fluid and for calculating this simulation, for this simulation we have considered this MR fluid in the static case okay. So for we have considered the MR fluid in the static case and in the same similar case actually we have done the simulation using Maxwell, Maxwell ansys Maxwell we have we did the simulation okay. So here this is the fixture here and 2 poles of the magnets are there and you can see magnetic lines of force from south pole to north pole it is moving from south pole to the north pole okay.

So it is passing through this MR fluid here. So along this line, along this line if we draw a line there along this line we can calculate the we can calculate the what is the along this line we can calculate what is the magnetic field okay along this line. So it is at a distance of x we can calculate here. So distance from x equal to 0 to 27. So this is the diameter of the cylinder, diameter of the workpiece cylinder here. So in between so distance between 2 workpieces there. So this is 27 millimeter.

So in between this 2 workpiece actually we can calculate this magnetic force. Also at the same time we have we have calculated the magnetic force we have calculated we have calculated the magnetic field at the same time we have calculated the magnetic field using gaussmeter also. So this dotted one you can see here. So this one is for N48 magnet and this one is for N17 permanent magnet okay. So these dotted one here this is the simulation results and experiment results at the bottom.

Here also experiment results at the bottom and top one is the simulation results. So we can see although this simulation results maximal simulation results is greater means higher than the normal case okay so in normal case you can see these abrasive particles are also there but in in our case actually we have not considered this abrasive particles okay. So that is why this in normal case there all this CIP particles are not CIP chains are not constant chains longer as continuous chains. There is a breakage is there but during simulation it is not considered okay. So it is considered as a homogeneous fluid okay.

So that is why simulation results we got the higher value. So but there is a very less difference in between the simulation and experimental results. So we can say that the results almost matching okay. So these are the 2 magnets, N17 and N48, 2 magnets are there, so cross section of this magnets, dimensions of the magnets are written here and magnet property this remnant magnetization corrosive force and B x max area of this B H curve okay. So this is also given. So these values are actually given as input to the permanent magnet for during this simulation Maxwell simulation. So from this Maxwell simulation we got this B E value, magnetic field value as a function of x. So this B E actually is required. Here it can we can put this value B here and if we get this B as a function of x we can get this dB dx okay.

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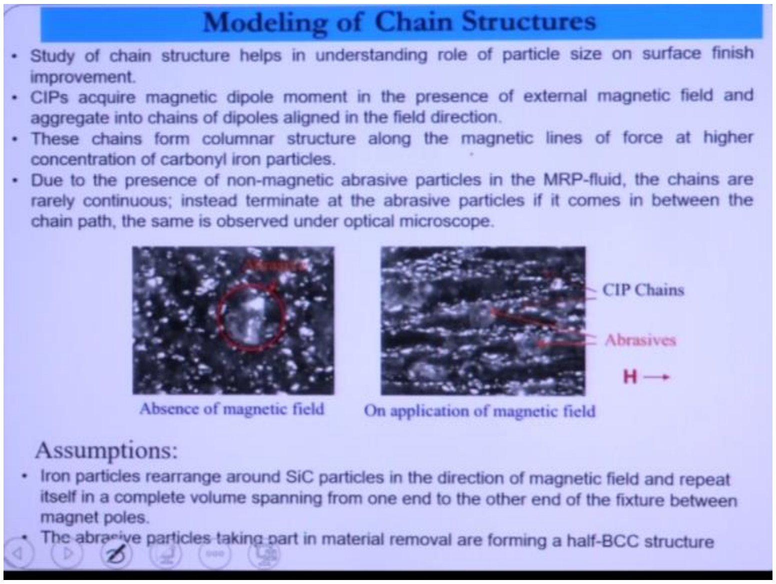

So modeling of chain structure now we have to model the chain structure okay. So study of chain structure helps in understanding the role of particle size on surface finish improvement. CIPs carbonyl iron particles acquire magnetic dipole moment in the presence of external magnetic field and aggregate into the chains of dipoles aligned along the magnetic field direction. These chains form the columnar structure along the magnetic field directions magnetic lines of force at higher concentration of carbonyl iron particles.

Due to the presence of non-magnetic abrasive particles this chains are not continuous chain so this these are the chains CIP particle chains are discontinuous chain because when abrasive particles are there it coming in front of the chain path so this chains actually breaks okay, so these chains are not continuous chains.

So iron particles the assumptions are there iron particles rearrange, rearrange around silicon carbide particles in the direction of the magnetic field and repeat itself in the complete volume spanning from one end to the other end of the magnet, so in between 2, 2 poles of the magnet. The abrasive particles taking part in the material removal are forming a half-BCC structure that we shall discuss here.

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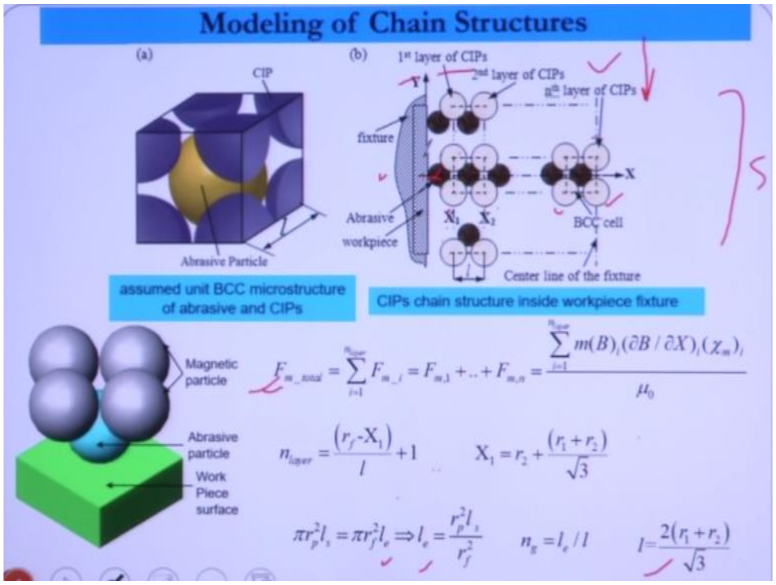

So here you can see this is the north pole here so here we have we have considered only one half of the fixture. So this is the central line of this fixture. Here the south pole will be there. So from north means from center to this point up to this workpiece fixture we can see these CIP particles are forming half-BCC structure and abrasive particles are kept in between this CIP structure, in between this carbonyl iron particle structure we have considered this abrasive particles.

Okay so these abrasive particles are actually indented into the workpiece surface. So it will give the indentation into the workpiece surface this abrasive particles it will give the indentation into the workpiece surface okay and when it is indented so we are giving this kind of axial force because of this axial force this indented material will be removed.

So now we have to calculate how much force is coming on this abrasive particles because this CIP chains are forming this layer from layer X1 to up to this layer, up to this final layer. So how many layers are there we have to consider okay. So from each layer actually this abrasive this CIP chains are contributing this force, magnetic force into this abrasive particles. So this total magnetic force can be calculated from layer 1, 1 to up to this final layer, layer n okay.

So these we know if we know this distance X1, X2 up to this X n so now we can calculate what should be the force okay. So these number of layers can be calculated as radius of the fixture minus X1 plus this l, this is the length, half-length of this BCC structure okay. So if we divided by this l will give the total number of layer and individual layer X1 can be calculated as this is the r2 is the radius of this abrasive particle plus r1 plus r2 by root 3, this is the half this portion from here to center to the center this is actually x means this r2 plus r1 plus r2 by root 3 this half of the distance of this half BCC structure.

So from here X1 can be calculated and then X2, X3 can be similarly can be calculated X1, X2 equal to X1 plus length of this BCC structure so like that up to Xn can be calculated. So now so there are 2 zones, one is the medium cylinder zone along the workpiece fixture zone. So volumetric flow rate should be constant along this media fixture, media along this media cylinder zone and the workpiece fixture zone okay.

So pi r p square total cross sectional area multiplied by the stroke length of this piston equal to pi r f square, r f is the radius of this fixture multiplied by this extrusion length okay. So now we can equate these 2 things. Now from there you can calculate what is the value of this extrusion layer. Now how many abrasive particles are there we can calculate. This extrusion length divided by this total means length of individual half-BCC structure, it will give the l e by l will give the how many abrasive particles are there.

So how many abrasive active abrasive particles so here one abrasive, another active abrasive, how many active abrasive. So total length, length of this extrusion length divided by this length of individual abrasive means individual half-BCC structure BCC structure, length of this BCC structure if we divide then we can calculate what should be the layers, how many active abrasive particles are taking part into the material removal. So this is the length of this BCC structure okay. So this is 2 r1 plus r2 by root 3.

So from here we can calculate this total force acting on this abrasive particles through CIP carbonyl iron particle chains okay.

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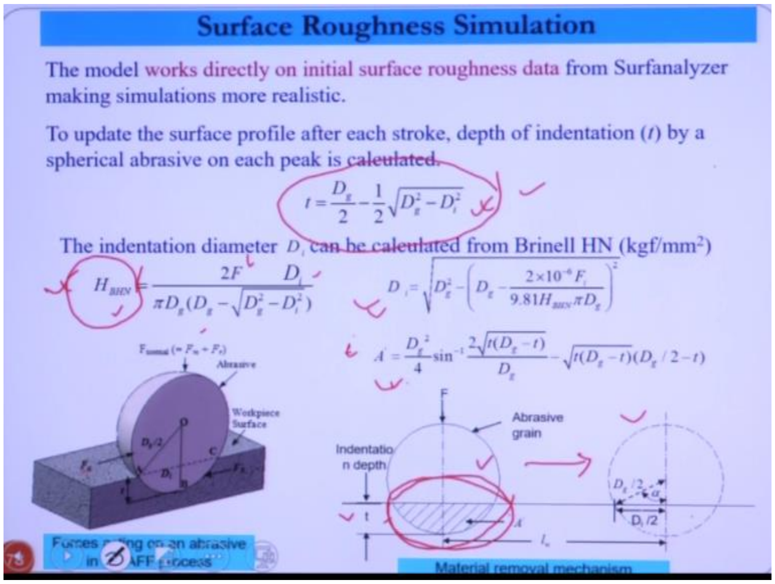

Now we have to calculate what is the depth of indentation. For calculating this depth of indentation we are considering the magnetic force plus radial force. So because of this magnetic force and radial force this abrasive particles are indented into the workpiece surface. Now you can see this half of this spherical sphere where we have considered this abrasive particles as a sphere here and model works directly on the initial surface roughness data whatever from Surfanalyzer whatever data we got.

So it works on the exactly same data on the same data of surface roughness data for making the simulations more realistic okay. So to update the surface profile after each stroke depth of indentation by a spherical abrasive particle on each peak is calculated. So depth of indentation we have to calculate how much depth it is indented, this abrasive particles is indented into the workpiece surface. So it can be calculated from this equation, from the geometry of this figure. So this is the abrasive particles is here.

So this is the cross section of the abrasive particle which is indented into the workpiece surface. So this is the depth of indentation. Now this abrasive particles actually it is sheared it is sheared into the workpiece surface and this much material will be removed from this workpiece surface. So this diameter of this abrasive particles is the D g and depth of indentation is t here, you can see this is the depth of indentation and diameter of this indentation is D i here okay. So now depth of indentation from the geometry of this figure you can calculate the depth of indentation okay. So now we know this for Brinell hardness number okay so if on a steel wall if you put pressure on a steel wall so this much will be the Brinell hardness number. So F is the normal indentation force on the on the steel wall okay.

So D g is the diameter of this wall and D i is the indentation diameter of this wall. So indentation diameter you can calculate from here okay. So if we put all these value and we know this Brinell hardness number of this of this workpiece material okay from there you can calculate the diameter of indentation. So depth of indentation and diameter of indentation we know and if we put these values of this depth of indentation and diameter of indentation into this equation you can calculate this how much material is removed by these abrasive particles.

So this much material cross section of this material is removed which is given by A dash by each abrasive particles. So this much material cross section of this material is removed which is given by A dash by each abrasive particles. Now it is when it is translated horizontally this much length multiplied by length will be this much material will be removed from the workpiece surface.

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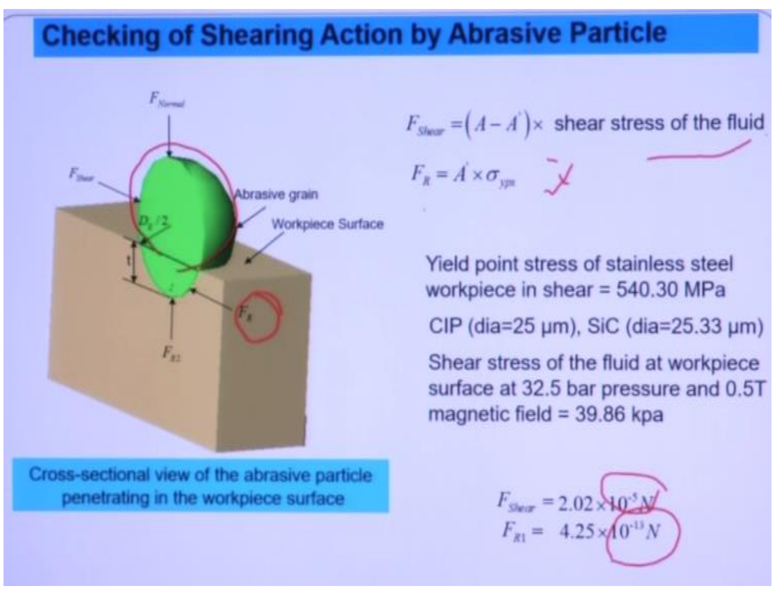

So here one more thing is that the shear force here this shear force on this abrasive particles should be greater than strength of this workpiece material. So this shear force acting on this abrasive particle should be greater than the strength of this workpiece material. This shear force can be calculated, A is the total cross sectional area minus this A dash is the cross means A dash is the cross sectional area which is indented into the workpiece surface. So this on this area actually your this shear force acting this shear force should be greater than this indentation this should be greater than the strength of this workpiece material okay so this shear force can be calculated here. A minus A dash into shear stress of this fluid and F R can be calculated this is the A dash here indented cross sectional area multiplied by yield point stress of this workpiece material. So F shear should be greater than F R.

So we have calculated this force, this F shear from our simulation magnetic field simulation we can see that here it is 10 to the power minus 5 N and this resistance offered by this workpiece material it is into the 10 to the power minus 13 N, it is very small. So this workpiece this abrasive particles are shearing to the or shearing to the from the workpiece material okay. So it is very very high, higher than the, this shear force is very very high than the strength of this workpiece material or resistance offered by the workpiece material okay.

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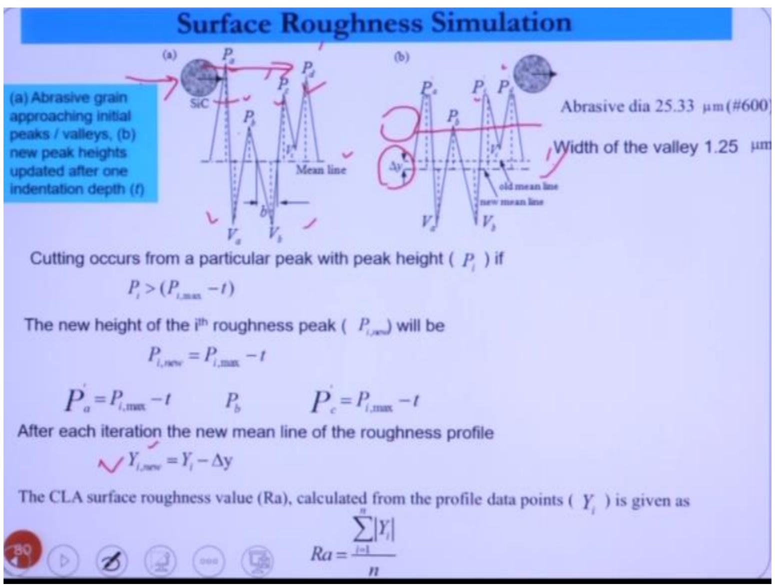

So now surface roughness we have to do the surface roughness simulation. So this surface roughness profiles it is taken from the instrument itself. So this instruments will give the peaks and valleys all this information will give. So this is the peaks are there so this different peaks are available here and these are the different valleys are available and this is the mean line here. So mean line is calculated. It is the average between the peaks and valleys okay.

So now this is the abrasive particle which is moving from left to right. So it will remove the surface undulations from the peaks here okay so from each and every peak it will remove the depth of indentation okay so it will not remove material from each and every peak. So suppose if this is the peak height is P a, P a minus t okay, so this much will be removed from here, this much will be removed from here, this much will be removed but from this P b it will not remove because we have considered this assumed that this abrasive particles will move in a straight line path because your shear stress is very high okay, shear stress is very high in our case. So this abrasive particles will move in a straight line path.

So after this cutting the peaks you can see P a this peak will become P a dash P c will become this P c dash and P d will become P d dash and then after some time when this abrasive particle will come here then only it will remove the peaks from P b also. So after that so each after each and every iteration this del Y there is a mean shift of del Y so mean this whole mean line is at the top after that it will be shifted at the bottom direction so this is the new mean line. So this del Y amount it will be shifted at every point.

So cutting occurs at every peak is P i greater than P i max minus t then only this cutting occurs otherwise there is no cutting. So after cutting we will see that these peaks values okay so Ra, Ra can be calculated from this Yi values all this new Yi values divided by number of peaks okay number of peaks and valleys this average value will give the surface roughness after each iteration.

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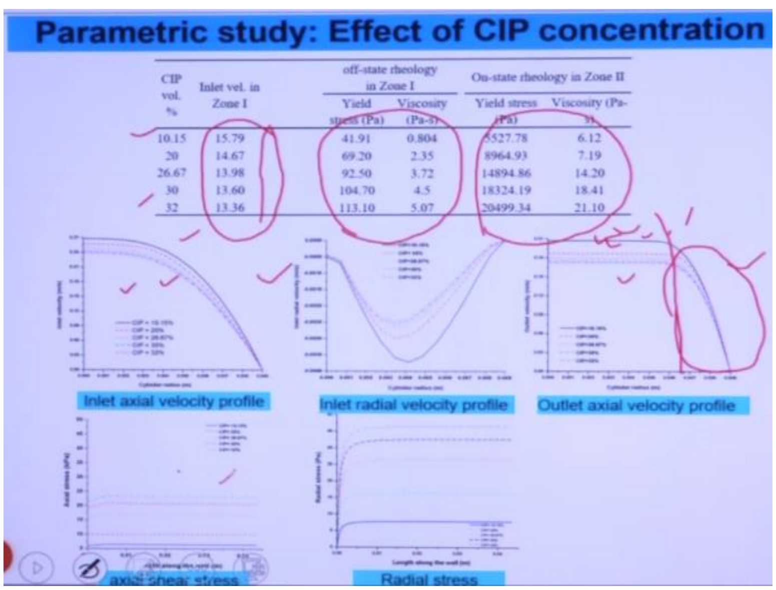

Now we have to do the parametric study at different CIP concentration, we have done parametric study from 10.15 CIP concentration up to 32 point CIP concentration. At every concentration we have measured the piston velocity okay so these are the piston velocity. With this uniform piston velocity at the zone I okay so yield stress of this fluid and viscosity of this fluid in zone I and zone II are actually it is calculated from the rheological study okay so from rheological study we have calculated this yield stress and viscosity in zone I and zone II and this inlet velocity it is calculated at different CIP concentration from the piston velocity. So this is the inlet velocity at zone I and radial velocity in zone I okay and this is the inlet velocity this is the velocity profile at the outlet at the outlet of this zone II.

So at this zone II you can see this kind of flat so this is one half of the fixture because we have considered the axisymmetry case so this is the one half of the fixture. So here up to this point you can see there is no change in the velocity gradient so velocity is constant okay so this portion is the solid core region and here this portion this portion here it is the this portion actually it is yielded shear zone okay.

So now you can see here velocity at higher at less CIP concentration is more at higher CIP concentration because when you are increasing the CIP concentration this CIP chain structure will become columnar structure and more strong chains will be formed so with the same pressure if you are flowing this speed its velocity will reduce with higher CIP concentration. Same case for this here also in the zone II also. So velocity will be higher for less CIP concentration than higher CIP concentration okay. So here you can see this axial shear stress also is higher, shear stress is higher for higher CIP concentration and also radial stress is higher for higher CIP concentration.

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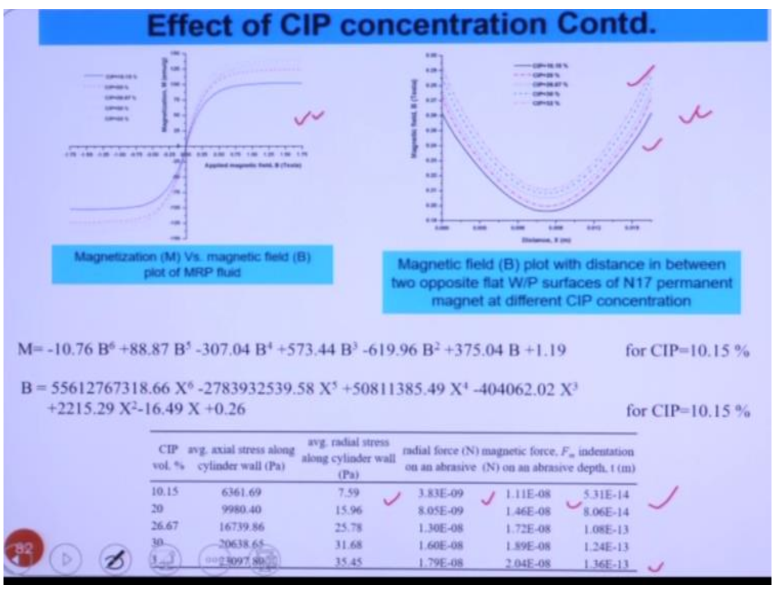

So with this information so now this NH curve also is drawn from VSM vibrating sample magnetometer and also this magnetic field analysis is also done at different CIP concentration okay. So at different CIP it is higher concentration it is lesser concentration so magnetic force also increases and you can from this information actually we can calculate the what is the average radial stress, radial force, magnetic force, and indentation into the workpiece surface. So you can see this indentation at higher CIP concentration this indentation in the 10 to the power minus 13 range on individual abrasive particles and at lower CIP concentration it is 10 to the power minus 14 range okay.

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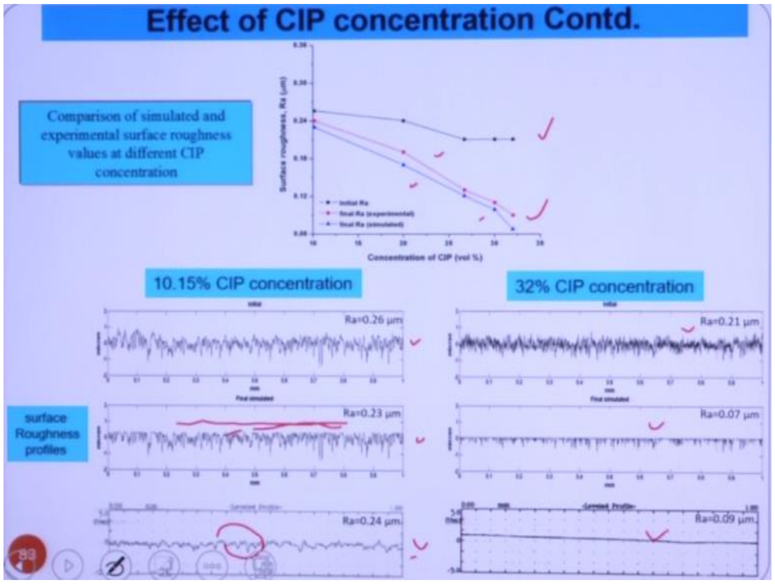

So now this is the initial workpiece surface, surface roughness profile, this is the final surface roughness profile, and this one is the experimental surface roughness profile. So now you can see this simulated surface roughness and experimental surface roughness profile almost matching here. So this is the initial surface at 10.15% CIP concentration. This surface roughness profile it is achieved, it is obtained from the surface roughness measuring machine.

On that profile actually we have done the simulation. So we can see this is the cut okay. So we can see this is the cut so this is the simulated surface roughness profile. So this is the experimental surface roughness profile after polishing. So here you can see this top portion is cut, peaks values are cut. Here also you can see this peak portions are somewhere it is cut here.

So this is the 32 CIP concentration you can see the initial surface roughness profile of 0.21 micron. This is the simulated surface roughness profile on this initial surface roughness. After simulation we got this 0.07%, 0.07 micron and after this experimental surface roughness profile it got 0.09 micron. So experimental we got higher we got experimentally we got this we got this higher surface roughness values.

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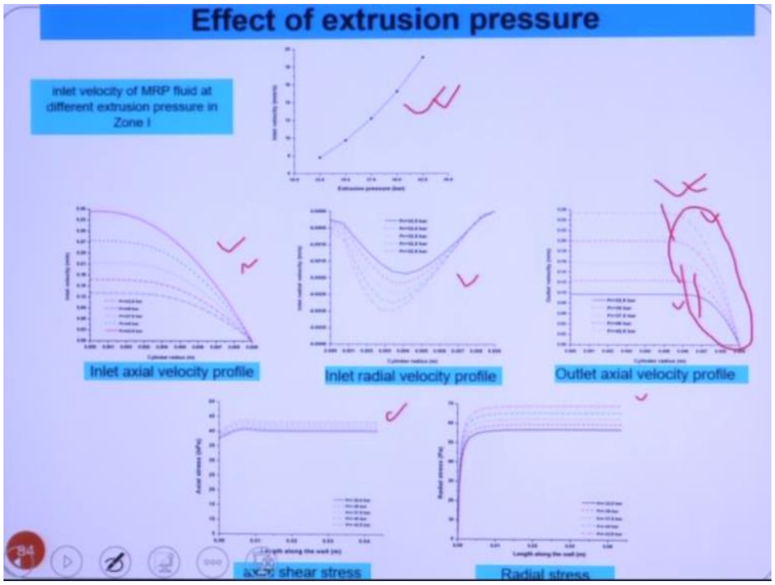

So after that we have done the parametric study for extrusion pressure also. At different extrusion pressure we have plotted the piston velocity. Using this piston velocity we have plotted the inlet velocity, outlet velocity from zone I, radial velocity, axial this is the axial velocity in at the outlet of this zone I, radial velocity at this outlet of this zone I, and this is the axial velocity at the outlet of zone II okay. So you can see here with so this is the less pressure and this is the high pressure. With high pressure you can see this solid core region actually reduces using the high pressure okay so because it is sheared.

So if we increase the shear most of the fluid at certain magnetic field at a constant magnetic field most of the fluid will be sheared and you can see there with the increasing in the pressure so you can see so with the increase in pressure your axial and radial stress also changes or increases here okay.

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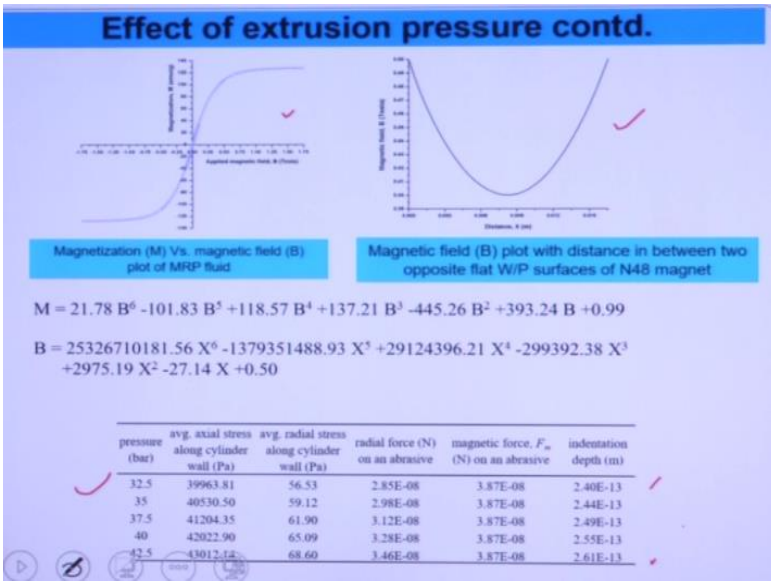

So because we are using in this case only single single fluid so at different pressure we are doing the experiments so this is the MH curve and this is the this magnetic field in between this 2 pole magnetic field plot in between the in between 2 workpieces or in between the 2 poles of the electromagnet. So at different pressures 32.5 bar to 42.5 bar pressure this indentation diameter you can see it is little bit increasing so there is not that much changes are there from 2.40 to we got this 2.61 into 10 to the power minus 3 range okay.

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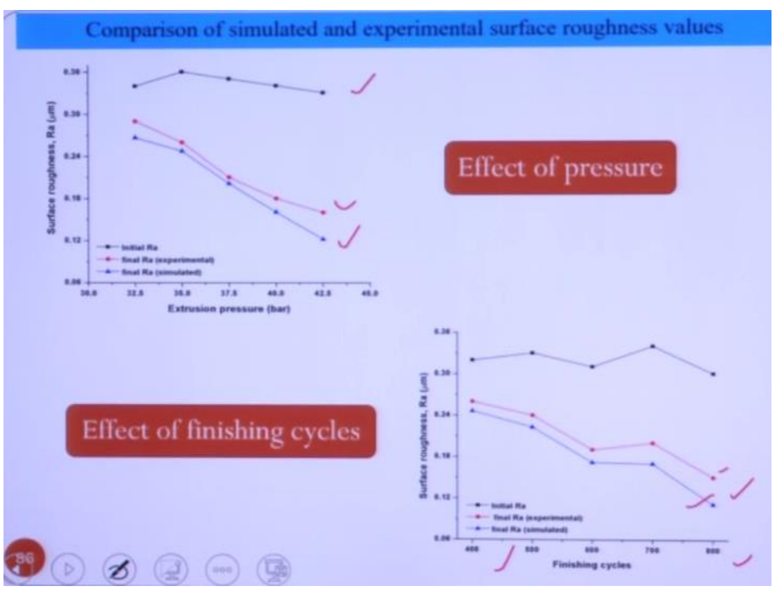

So with the increasing pressure we can see surface finish also improves. This is the initial surface roughness profile, this is the final surface roughness profile, and after that this is the experimental surface roughness profile. After that we have done the experiments on finishing cycles also, 400 finishing cycles to 800 finishing cycles. So you can see almost similar final surface roughness profile, simulated final surface roughness, and this is the experimental final surface roughness profile, almost they are matching okay.

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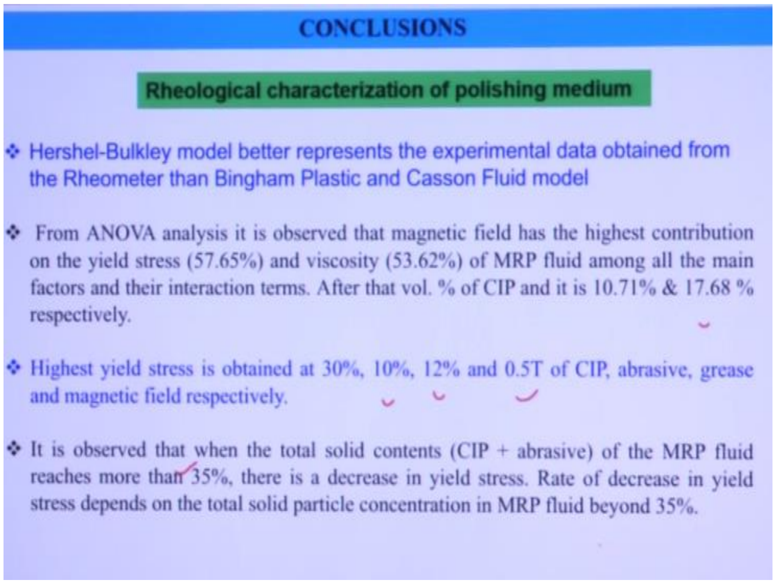

So these are the conclusions from our experimental study. Rheological characterization, from rheological characterization we have seen that Hershel Bulkley model actually better represents the experimental data obtained from the rheometer and Bingham plastic then Bingham plastic and Casson fluid models and from Anova analysis we have seen that magnetic field has the highest contribution on yield stress and viscosity of MR fluid and from all the main factors and interactions.

So we have considered this 10.71 and 17.68. So these are the after that CIP concentration okay contribution of the CIP concentration and highest yield stress is obtained for 30% CIP, 10% abrasive, 12% grease and 48% paraffin oil at 0.5 tesla magnetic field. So it is also observed that when the total solid contents CIP plus abrasive of the MRP fluid reaches more than 35% there is a decrease in yield stress. So rate of decrease in yield stress depends on the total solid particles concentration in MRP fluid beyond this 35%.

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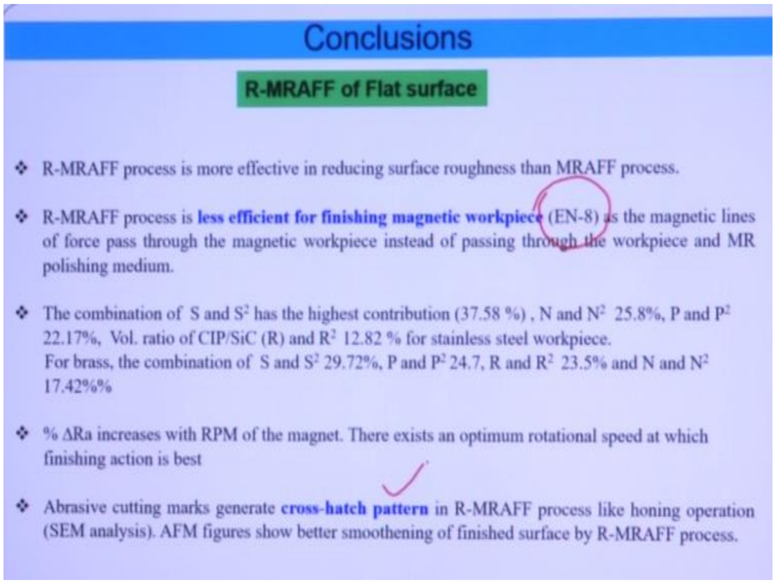

So from rotational MRAFF process of flat workpieces so R-MRAFF process is more effectively reducing the surface roughness than MRAFF process. R-MRAFF process is less efficient for finishing magnetic workpiece EN-8 workpiece okay and the combination of S and rotational speed of the magnet and square of the rotation speed of the magnet highest contribution has the highest contribution okay.

So percent change in Ra increases with the rotational speed of the magnet. After that it reaches to an optimum value and then it reduces because of this shear thinning fluid shear thinning nature of the fluid and also abrasive particles cut marks generates cross-hatch pattern on the workpiece surface okay it generates cross-hatch pattern.

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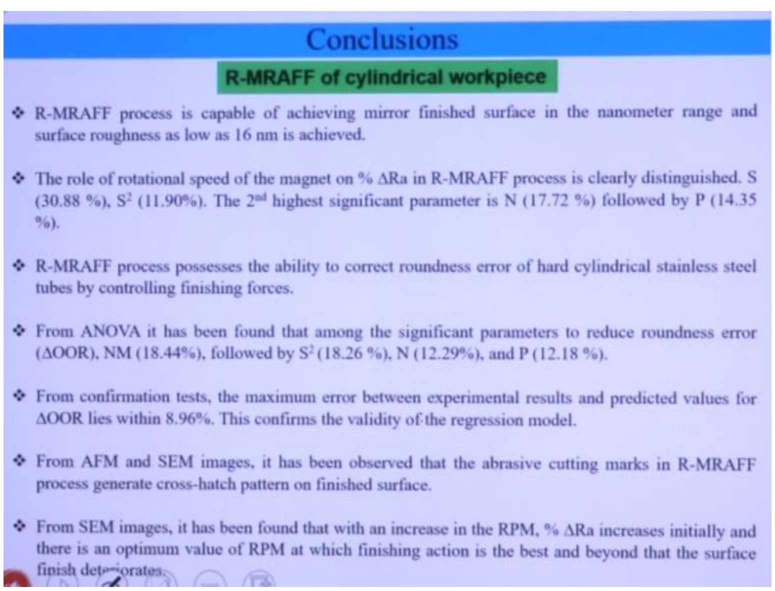

And then from cylindrical workpiece also we got that it is capable of polishing cylindrical workpiece, cylindrical stainless steel workpiece. Also it can reduce the out-of-roundness of this workpiece, cylindrical workpieces okay. So from abrasive flow atomic force microscope and scanning electron images we have seen that abrasive particles give the generates cross-hatch pattern on the workpiece surface which helps in oil retention okay.

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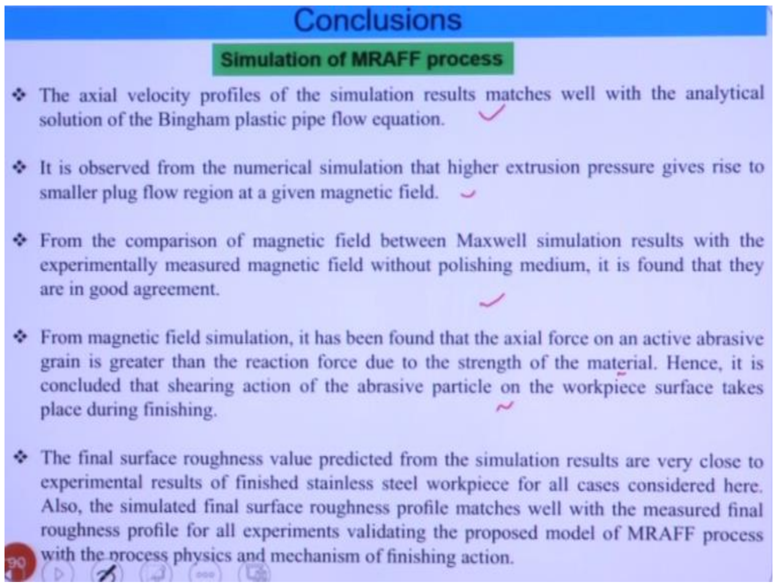

So simulation from MRAFF process compressional fluid dynamic simulation of MRAFF process so this axial velocity profile of the simulation results matches well with the analytic solution of Bingham plastic pipe flow equation. It is also observed that numerical simulation higher extrusion pressure that higher extrusion pressure give rise to a smaller plug flow region at a given magnetic field. From the compression of magnetic field between Maxwell simulation results with the experimentally measured magnetic field without polishing medium it is found that they are in good agreement.

From the magnetic field simulation it is it has been found that this axial force on an active abrasive grain is greater than the reaction force due to the strength of this material. Hence it is concluded that shearing action of the abrasive particle on the workpiece surface takes place during finishing and also this final surface roughness values predicted from the simulation results are very close to the experimental results of the finished surface for experiments at different CIP concentration at different workpiece extrusion at different extrusion pressure okay.

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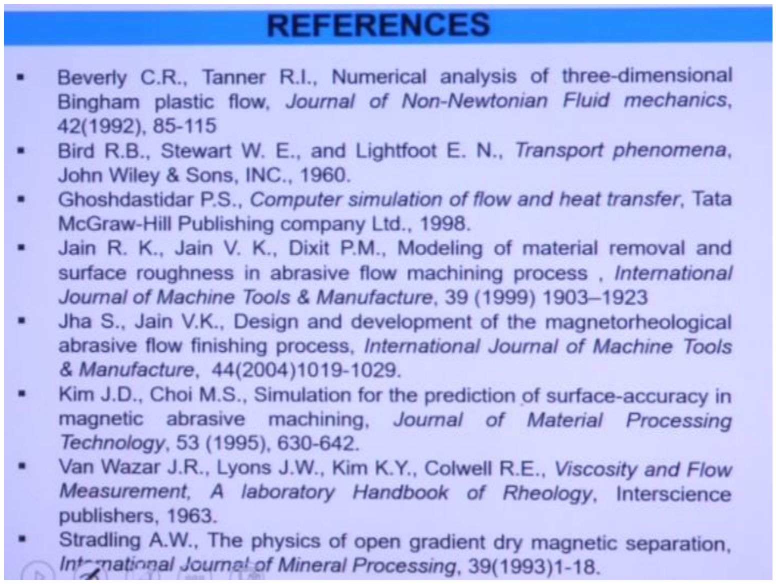

So these are the references are there and thank you.