Advanced Machining Processes
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Module - 04
Lecture - 09
Magnetorheological Abrasive Flow Finishing (Part 1)

Welcome to the course on advance machining processes. Now we are going to discuss one habit process that is called rotational magnetorheological abrasive flow finishing process or in brief we can say this one as R-MRAFF process. So this is the outline of my presentation.

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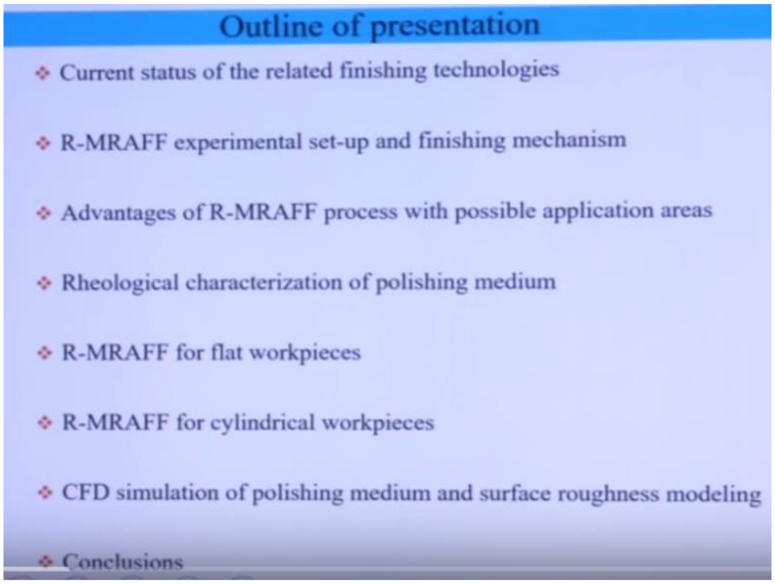

So what are the current status of this finishing processes and then R-MRAFF rotational magnetorheological abrasive flow finishing experimental setups and finishing mechanism we shall discuss. Then we shall discuss about the advantages of R-MRAFF process with possible application areas and then rheological characterization of polishing media.

Then we shall discuss about the finishing experiments using flat workpiece R-MRAFF finishing experiment with flat workpiece. Then we shall discuss R-MRAFF finishing experiment with cylindrical workpiece, internal surface of cylindrical workpiece. Then we shall discuss some CFD simulation computational fluid dynamic simulation of polishing medium and surface roughness model. Then we shall conclude.

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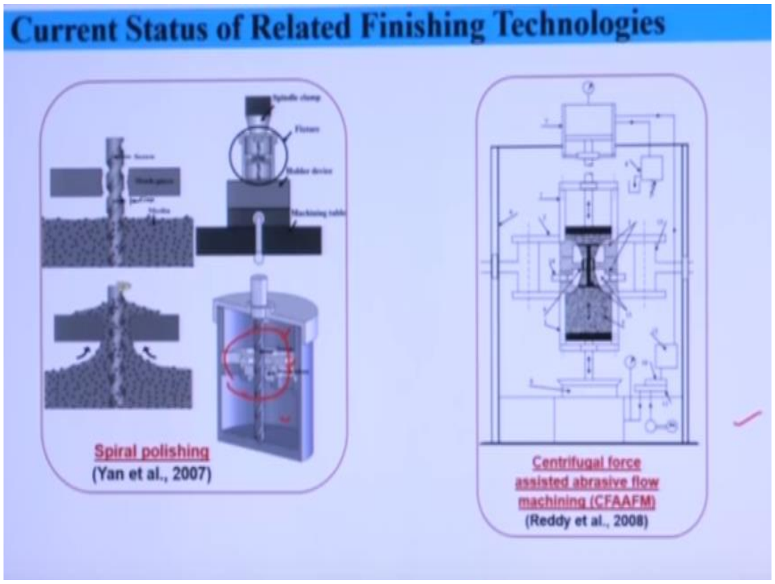

Now this current status of the related finishing technologies you can see here this is the spiral polishing which is developed by Yan et al., at 2007 okay. So here you can see one spiral tool is there okay. So this spiral tool. So this is the bottom chamber. This is the top chamber okay. So this initially this bottom chamber it is filled up with the polishing medium, viscoelastic polishing medium, as the spiral tool is there as the spiral too rotates okay so this polishing medium it will through the groove of the spiral tool it will try to come to the top media cylinder okay.

So while coming to the top media cylinder if you keep workpiece over here so if you keep workpiece over here okay so it will remove the surface undulation or polish the workpieces there. So this is the fixture here so in this, this is the fixture here. In this fixture you have to keep the workpiece. Obviously this workpiece, internal surface of the workpiece you can polish by this process. So when media is coming from the bottom media cylinder to the top media cylinder while coming while passing through this workpiece fixture okay through this workpiece and workpiece fixture assembly it will polish it will polish or removes the surface undulations from the workpiece surface.

So this is the one of the mechanism to polish internal surface of the workpieces. So here this is the centrifugal assisted abrasive flow mechanism CFAFF so it is developed by Reddy et al., 2008 at IIT Roorkee okay. So this is the similar to the AFM process. What they have done? They have actually used one centrifugal rod there at the center okay. So at the media cylinder through the workpiece they put one cylindrical rod or centrifugal rod. So as the centrifugal rod rotates, they are rotating the centrifugal rod outside from outside.

As the centrifugal rod rotates, because of the centrifugal force the internal surface of the workpieces actually removes okay. So here there are 2 forces, 2 actions are there. This centrifugal rod is rotating and at the same time they are giving reciprocating motion of the polishing media. So because of this action of this 2 process here the surface finish improves which is better than normal AFM process, abrasive flow finishing process.

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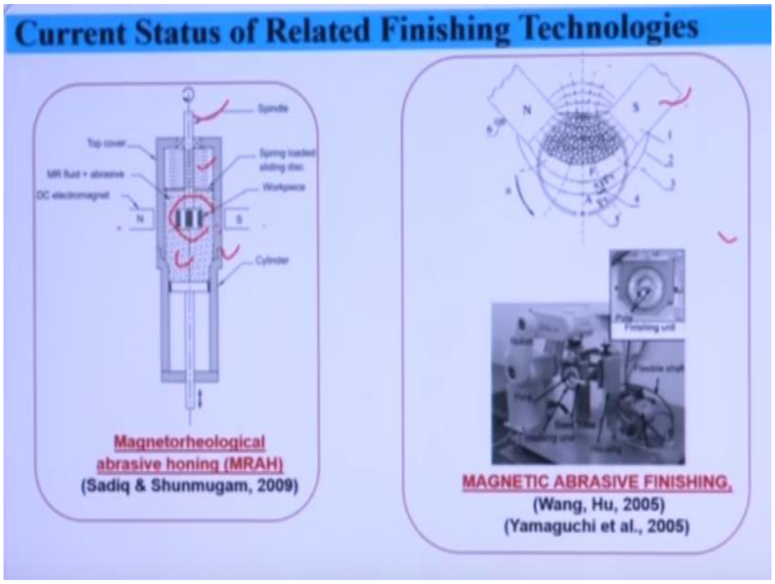

Now this is the magnetorheological abrasive honing, MRAH abrasive honing operation by Sadiq and Shanmugam so in 2009 it is developed at IIT Chennai here. So here this is the container here. Inside that container they filled up with the MR polishing fluid. So this is this container is just filled up with the MR polishing fluid. So there is a cylindrical fixture here. This cylindrical fixture at the external surface of the cylindrical fixture they kept their workpieces there.

Now this workpiece actually rotated by external means here. So it is rotated by an external means and now they have applied some magnetic field here. So when they are applying this magnetic field this MR polishing fluid here it will become very stiff here at this zone, MR polishing fluid will become very stiff okay. So now this MR polishing fluid will remove the surface undulations from the workpiece surface here okay.

So they are giving reciprocating motion also by using this spring mechanism okay, spring and plunger mechanism they are giving some reciprocating motion to the polishing media. So they are giving reciprocating, they are reciprocating as well as rotating the workpiece inside okay. Now this magnetic field they have used this magnetic field here. Because of this magnetic field this MR polishing fluid will become stiff at this zone only okay at the finishing zone okay and as the as they are giving the reciprocating motion so it will remove the surface undulations from the workpiece surface.

So this right hand side picture you can see this is the magnetic abrasive finishing process, Wang, Hu, they developed this one in 2005 and Yamaguchi et al., also they did some experiments over this machine in 2005 in Japan. So you can see here they are polishing a bent tube okay. So this bent tube actually they are polishing. So for polishing so this kind of this magnets actually they kept 90 degree with each other okay.

So you can see here in magnetic abrasive finishing, this moves magnetic abrasive particles and abrasive particles are there they will form the lines of force, magnetic lines of force they will form chains along the direction of magnetic lines of force and this is the equipotential line you can see so this now they are rotating this workpiece now okay or you can rotate the this total assembly also this magnet assembly also you can rotate from outside.

So what they have done, they are rotating this magnet assembly. Also they are moving this magnet assembly by using a robotic arm. So by using a robotic arm, they are moving this magnet assembly okay and at the same time at the same time they are rotating also this total magnet assembly they are rotating.

So because of the this whatever the polishing media is there it will remove the surface undulation or polish at the internal surface of the cylindrical workpiece. So this is one of the mechanism to polish internal surface of the workpiece.

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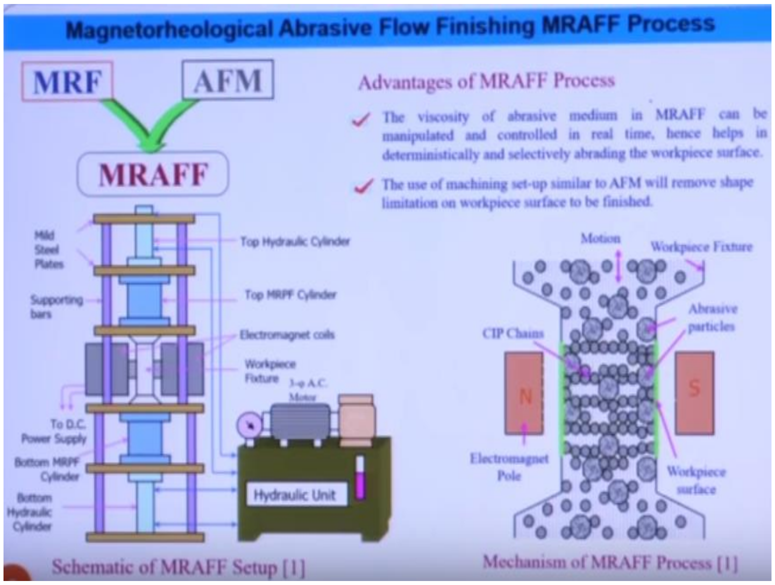

Now after that magnetorheological abrasive flow finishing process which we discussed in the last class which is consist of MRF process and AFM process okay so it is developed so by taking advantage of both the process magnetorheological finishing process and abrasive flow finishing process, so they have taken the advantage of both the processes here okay. So what are the advantages are there. So advantages are viscosity of the abrasive polishing media.

So we can control from outside by using applying magnetic field. So you can control this viscosity of this media from outside by using the applied magnetic field and also this experimental setup as it is similar to the abrasive flow machining setup okay, so in abrasive flow machining setup you can polish any kind of complex geometrical surface either it is internal or external any kind of polishing surface you can any kind of surface you can polish okay. So as the machining setup it is close to the, it is similar to the abrasive flow machining okay. So there is no safe limitation on the workpiece surface to be finished.

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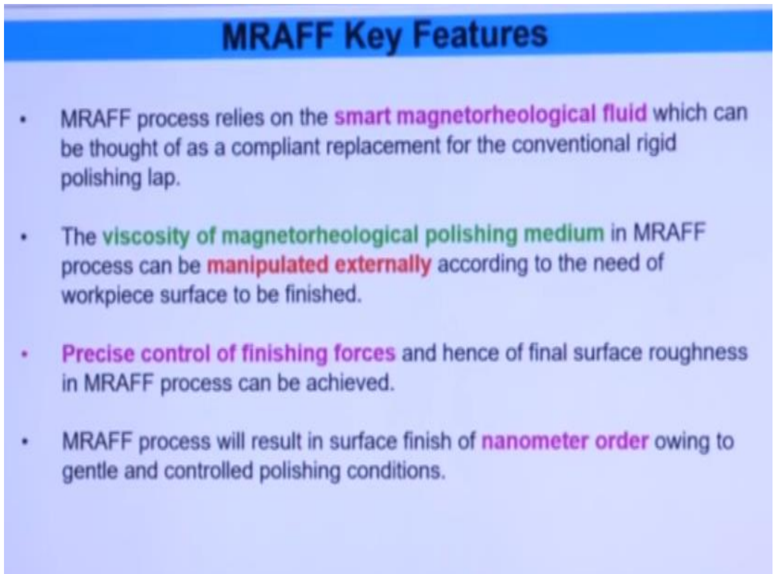

Now this is the key features of the MRAFF process. So MRAFF process relies on the smart magnetorheological fluid which can be thought of as a compliant lap for replacement for the conventional rigid polishing lap. The viscosity of the magnetorheological polishing medium in MRAFF process can be manipulated externally according to the need of the workpiece surface to be finished and precise control of finishing forces and hence the final surface roughness in MRAFF process can be achieved.

You can precisely control the finishing forces by changing the pressure or by changing the magnetic field okay. MRAFF process will result in a surface finish of nanometer range owing to the gentle and controlled polishing conditions. So you can get the surface finish in the nanometer range by using MRAFF process.

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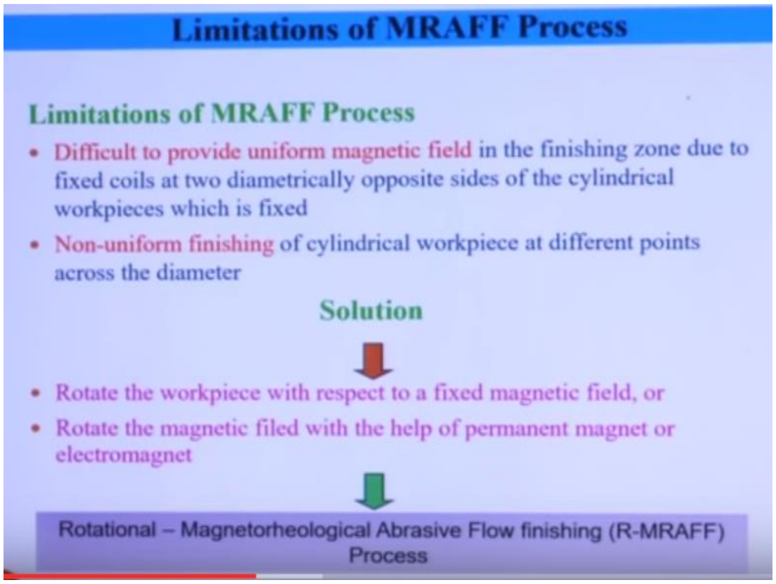

But it has, this MRAFF process has certain limitations. So you can see that magnetic field whatever 2 coils of the magnets which are applied just opposite to the each outside the cylindrical workpieces, in that case we can see there this core materials this core materials are just opposite to each other on a cylindrical workpiece and most of the magnetic field will be there where this core materials is there or north pole and south pole is there.

Just perpendicular to that where you are not applying magnetic field vertically into that surface there you will get the less magnetic field. Although this core material is covering the total cylindrical surface but perpendicular to that surface you will get less magnetic field or at the internal surface of this cylindrical workpiece you will find that non-uniform magnetic field somewhere this magnetic field is more and somewhere this magnetic field is less.

So first limitation is the difficult to provide uniform magnetic field in the finishing zone due to the fixed coils at 2 diametrically opposite sides of the cylindrical workpieces which are fixed. Now non-uniform finishing of cylindrical workpiece at different points across the diameter. So that is why there is a non-uniform polishing because of the non-uniform magnetic field. So non-uniform polishing, if you are polishing a cylindrical workpiece or different cross-sections also if you are not giving magnetic field uniformly surrounding this cylindrical workpiece you will get non-uniform polishing from the workpiece surface.

So what is the solution here? The solution is that rotate the workpiece with respect to the fixed magnetic field. So you can rotate the workpiece here or you can rotate the magnetic field itself or rotate the magnetic field with the help of a permanent magnet or electromagnet. So you can rotate the workpiece or you can rotate the magnetic field from outside okay. But in case of MRAFF process as we are using the oil based media so there is a leakage problem. So if you try to rotate the workpiece there in MRAFF process, there will be this MRAFF will leak out okay, it will come outside okay.

So because we are applying used pressure and our fluid is in the liquid state only there while we are applying magnetic field it will become almost solid but in other places it is becoming Newtonian fluid, it is like a Newtonian fluid. So if you try to rotate the workpiece here it is not a feasible one okay. So that is why we have thought of rotating the magnetic field itself surrounding the workpiece okay. So by giving this concept by giving this concept we have developed a new process which is called rotational magnetorheological abrasive flow finishing process. So this is called rotational magnetorheological abrasive flow finishing process.

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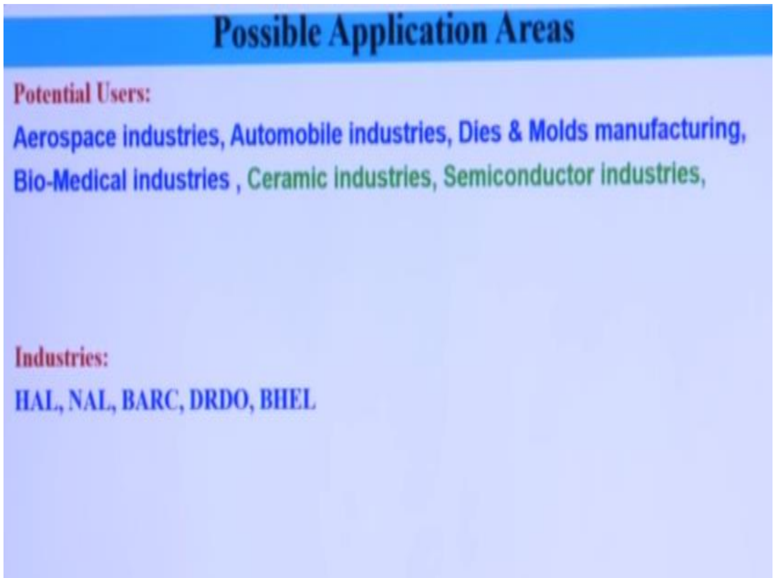

So what are the possible application areas? So it has applications in aerospace industries, automobile industries, dyes and mold manufacturing industries, bio-medical industries, ceramic industries, and semiconductor industries. So all these industries it can it can be used for polishing very small components, any intricate components, any non-uniform components, internal surface, inaccessible areas of the components can be polished by this process.

So industries, these are the industries, HAL, NAL, BARC, DRDO, BHEL may be interested to use this process for polishing of their intricate components.

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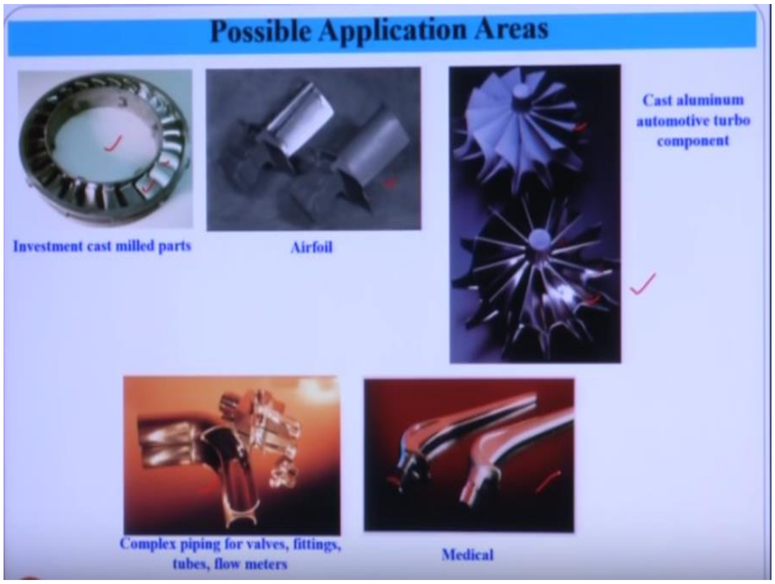

Okay, these are the possible application areas. So now first one you can see here. This is the investment cast milled parts. Here these are the curvatures on the component you can see. These curvatures non-uniform surface on the on this non-uniform surface of this components are there. So these components can be polished by the MRAFF process by flowing this media through this through this components.

So this is the airfoil which has a very complicated surface, this airfoil. This airfoil, through this airfoil you have to put, you have to flow this media in such that it will remove the surface undulations from the airfoil surface. So this is the cast aluminium component, aluminium automotive turbo component okay. So this is the cast aluminium automotive turbo component is there. So this component you can see at the surface it is a non-uniform surface is there.

So this is the initial surface, this is the polished surface okay. So this kind of surface can be polished by this R-MRAFF process. So this kind of bent tubes which are used, complex fitting of valves, fittings, tubes, flow meters okay. So this kind of bent tubes are used in medical equipments also. So this bent the internal surface of the bent tubes can be polished by this R-MRAFF process and this this kind of medical components are there. So this components also can be polished by this R-MRAFF process.

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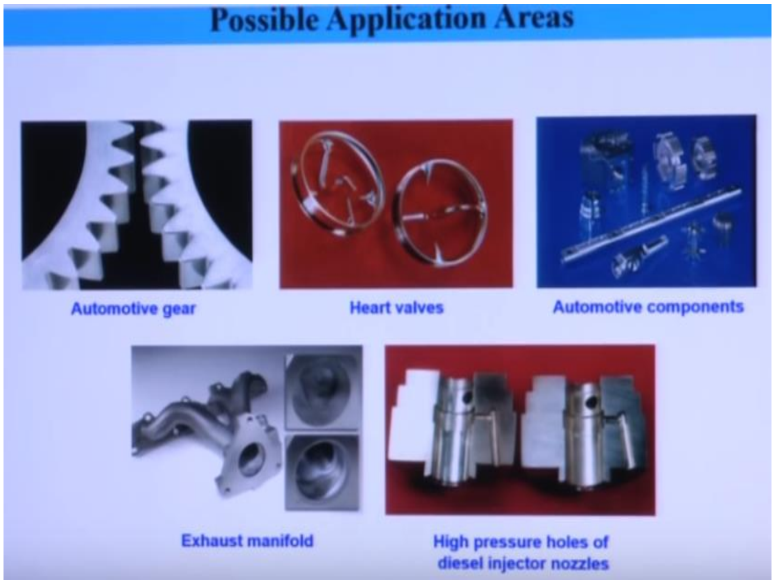

Suppose gears are there. So at the mating surface of this gears you will see there are some small small bars are available, bars are there. During milling of this gears, so this bars are actually generated. Unless you remove this bars this gears you cannot use. If you are making very small gears this bars size is if it is very high in that case it will not match at all okay.

So there will be (()) (16:08) all these things will be there if you use this kind of defective gears. So this gear tip can be polished by this rotational magnetorheological abrasive flow finishing process by flowing the media in such a way that you have to flow the media through the teeth only okay. So second one is the heart valves. This kind of heart valves are used in medical industries. So this heart valves it should be highly polished okay.

So these heart valves can be polished by rotational MRAFF process. So thousands of automatic components, these components can be polished by this R-MRAFF process. Like exhaust manifold of engine okay. So there are intersection of various intersection of various fluids are there, various cylindrical channels are there. So at this intersection too is the flow of the fluid. So you have to remove the material from the at the internal at the intersection surface okay. So rotational MRAFF process can be used for polishing this kind of fluid, this kind of workpiece. So high pressure holes of diesel injector nozzles. So this also can be polished by R-MRAFF process.

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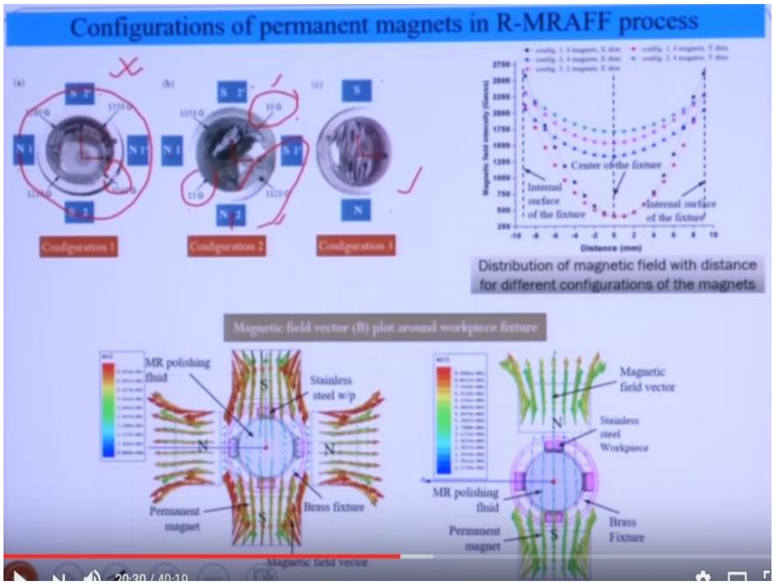

So these are the different configurations of the magnet. So we have used permanent magnet initially. So different configurations we have thought of so that at which configuration we will get uniform polishing at the internal surface of the workpiece so that configuration can be used for polishing all the workpieces.

So these are the 3 configurations we have thought of. This is the first configuration you can see here. This is the south pole and this is north pole here. So in between you can see this CIP iron particles chains are actually forming in between this south pole and north pole okay. But here you can see this magnetic field is not uniform inside the workpiece. So it is, magnetic field, it is not uniform inside the workpiece. So we have considered a cylindrical replica. It is made of phosphates okay so these this replica it is made of phosphates and it is filled up with MR fluid. Now we have applied some magnetic field there. Now we are seeing observing the chains okay. So you can see this chains are not uniform in case of in configuration 3.

Now you come to this configuration 1. So in this configuration you can see this north pole, south pole, north pole, south pole like that we have used. So now we can see here, here at this point these points actually it is just 45 degree to both the north and south pole here. You can see this magnetic fields are almost uniform okay 1208, 1280 gauss, 1550, 1049, 1230 gauss. So magnetic field is uniform in this case okay.

So now if we rotate this total assembly here, if we rotate this total permanent magnet assembly, we will get the uniform polishing at the internal surface of the workpiece. So this is the configuration 2, second configuration where this north pole and south pole this combinations are kept and here this north pole and south pole this combinations are kept. So that is why magnetic field, magnetic chains are actually forming in between this north and south pole. Here also magnetic lines of force are forming in between this north and south pole.

So here also you can see in second one this magnetic field is not uniform at the internal surface. So here at the 45 degree you can see it is 10 gauss, 1050 gauss, 15 gauss, and 1120 gauss. So here at this point magnetic field is very less. But in this configuration everywhere this magnetic field is almost similar and it is high also okay.

So also we have measured the magnetic field using a gaussmeter, gaussmeter is a device which is used for measuring the magnetic field okay. It has a hall probe, hall sensor, hall probe sensor. That sensor you can you have to keep where you want to this is the flat, flat sensor is there, so perpendicular to the magnetic field you have to keep your hall sensor, hall probe sensor okay and it will show the how much magnetic field it is crossing, it is it is crossing that area is crossing. So at that point what is the magnetic field intensity it will it will measure.

So from all the configurations here after measuring after measuring magnetic field in between this north and south pole okay, so we have found that this configuration 1 here in this case we got highest magnetic field okay, we got highest magnetic field in this case than configuration 2 and 3. So this configuration 1 is actually considered for this configuration 1 is considered for measuring for doing the R-MRAFF experiments.

So here also we have done some Maxwell simulation, ANSYS Maxwell, we have simulated this MR fluid inside this fixture. Similar to that fixture workpieces here you can see these workpieces are actually stainless steel workpieces are kept at the internal surface of this fixture. Now we have to apply magnetic field outside. Now we can see this how this uniformly this magnetic fields are distributing per this configuration 1 and this is per configuration 3. So we can see at configuration 1 you will get the highest magnetic field at the internal surface.

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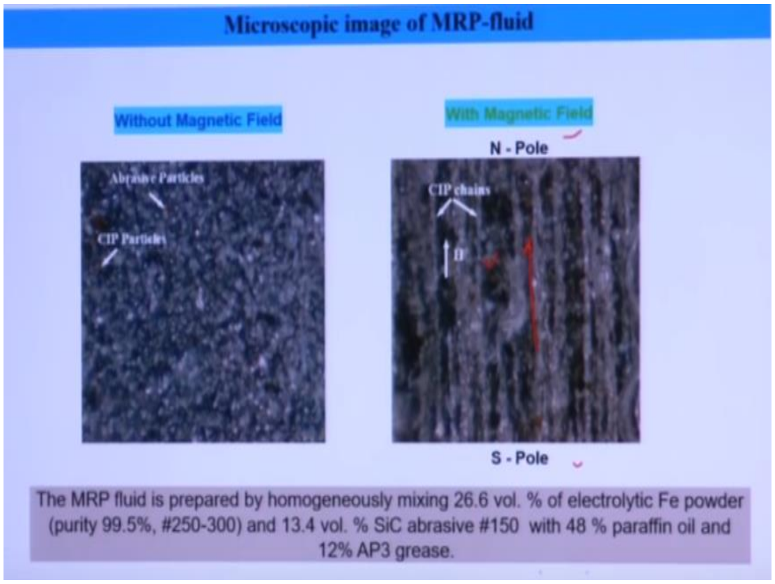

So this is the microscopic image of the MR polishing fluid, magnetorheological polishing fluid. So as I told it consist of CIP particles and abrasive particles. So it consist of carbon and iron particles and abrasive particles here. You can see this abrasive particles here and you can see these CIP particles here okay, so without the application of magnetic field.

Now when you are applying some magnetic field and this is your north pole and this is your south pole here when you are applying some magnetic field here this iron particles are forming chains along the magnetic field direction so this is the direction of this magnetic field. This iron particles are forming chains and in between this chains you can see this abrasive particles are held in between these chains.

So here clearly visible these chains are forming. This MRP fluid is prepared by homogeneously mixing 26.6% of electrolytic iron powder, purity 99.5%. So here mesh size is 250 - 300 mesh size and 13.4 volume % of silicon carbide abrasive with 150 mesh size with 48% paraffin oil and 12% AP3 grease.

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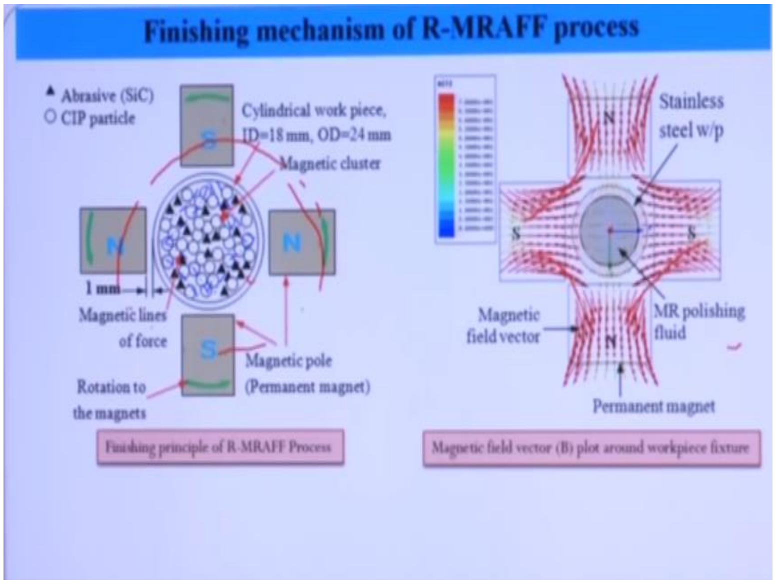

So now here you can see schematic diagram. So now this north pole, south pole, again north pole and south pole this configuration 1 we have considered okay. So this configuration along the means in this configuration all these permanent magnets are kept and this is the workpiece, fixed workpiece here. So here workpiece how along the magnetic lines of force how these iron particles are forming and this black colours are actually abrasive particles okay.

So this abrasive particles are held in between this CIP chains here. Now you are rotating this magnetic field. So this this total assembly permanent magnet assembly or fixture permanent magnetic fixture it is rotated in between 2 bearings. When it is rotated it will generate a, when it is rotated it will generate a realty motion okay in between the workpiece, internal surface of the workpiece and the fluid and then fluid will also rotate because we are applying this magnetic field this inside this inside this workpiece this workpiece also will rotate and due to the relative motion between the abrasive particles and the internal surface of the workpiece it will remove the surface undulations from the workpiece surface.

So here you can see this how this magnetic vector lines are forming in case in configuration 1. So these are the vector lines are there. So here from south pole to north pole and south pole to north pole again south pole to north pole here south pole to north pole. So these are the vector lines. So it is you can see here it is in from magnetic field is generated in case of R-MRAFF process.

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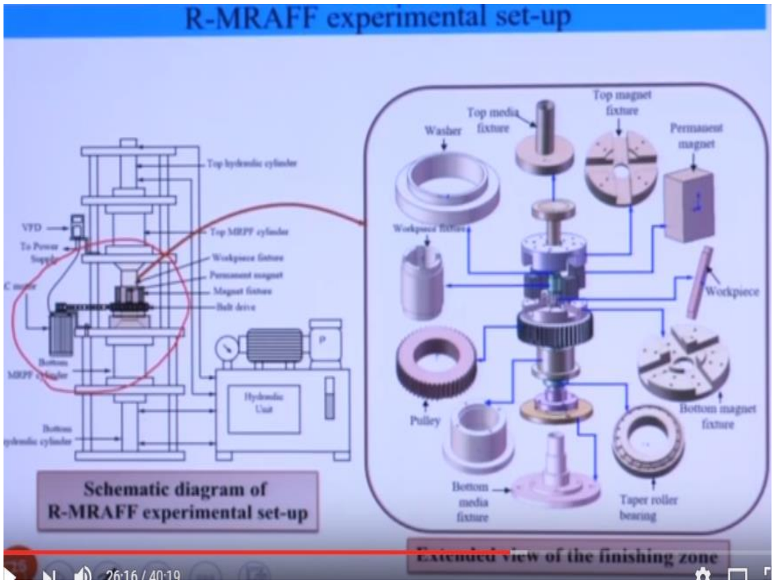

So this is the extended view of the experimental setup. So same magnetorheological abrasive flow finishing experimental setup MRAFF experimental setup, it is retrofitted. Here it is this zone only actually we have modified. Here what we have done? Inside a fixture, so we have we have developed a fixture to fix the permanent magnets. So you can consider there is a cylindrical fixture is there. There is a cylindrical fixture. So in that cylindrical fixture we kept some slots.

Inside that slots we kept our permanent magnets inside that slots we kept our permanent magnets. Now this total fixture magnet fixture actually it is rotated. When this magnetic fixture is rotated using a motor okay. So MR fluid because of this magnets are rotating MR fluid inside the fixture also will rotate because of the relative motion between this abrasive particles and the workpiece surface it will remove the surface undulations and because of this magnetic field this CIP chains will form okay. CIP chains are chains will form and this abrasive particles will be held in between these chains.

Now because of this rotation there is a chance that this abrasive particles will homogeneously mix up inside that workpiece and workpiece fixture okay. So new phrase abrasive particles will come as an active abrasive particles it will come towards the workpiece okay. It will act as a active abrasive particles. So this is the extended view of the fixture. Now this fixture, this magnet fixture it is rotated using a belt drive using a motor it is rotated. So we have used positive belt drive here.

This is the pulley, 2 pulleys are there, you can see these 2 pulleys okay. So there is a variable frequency drive. So by changing the frequency to the current frequency of the current by changing the frequency of the current you can rotate this motor at different RPM okay. So we have rotated this motor at different RPM by changing the frequency in the variable frequency drive. So this is the hydraulic unit already we have discussed in abrasive in MRAFF process we have discussed okay. So these are the so many components are there. So this is the workpiece here. This is the workpiece, cylindrical workpiece we kept here inside okay and outside we have kept this magnets, magnet fixture.

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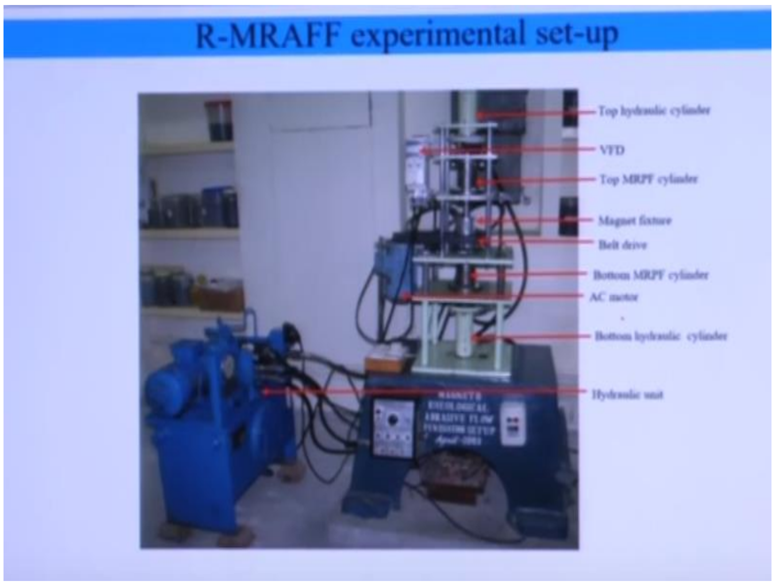

So now this experimental setup looks like this, this R-MRAFF experimental setup it looks like this.

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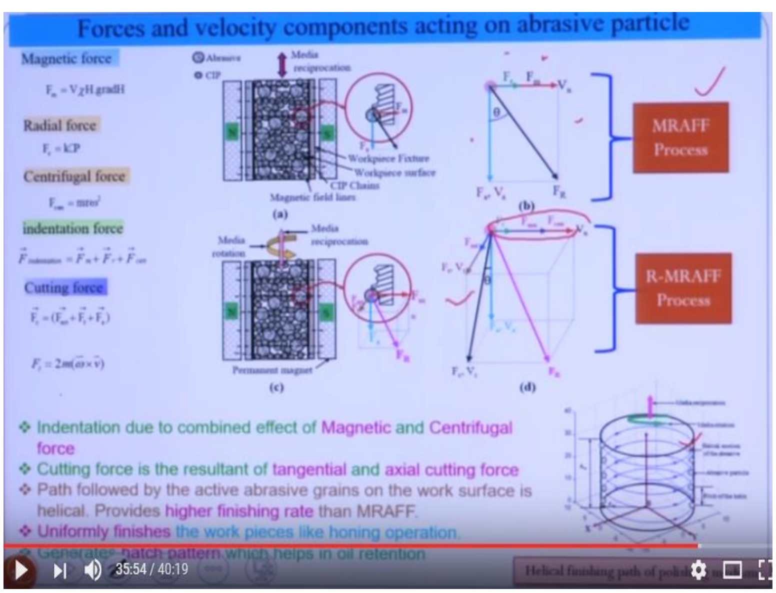

So now what is the advantages of rotation? So how many forces are there? So what we have discussed in MRAFF process because of this reciprocating motion one radial force will be generated and one axial force will be generated because of this reciprocating motion and magnetic force also will be generated so this magnetic force direction of magnetic force and radial force both are in the same direction. So this magnetic force is perpendicular to the workpiece surface okay.

So what is the what is the how much magnetic field magnetic force will be generated it is V chi H into gradient H, H is the applied magnetic field, chi is the magnetic susceptibility and V is the volume of the fluid. Then radial force, it is proportional to pressure how much so radial force in case of this MRAFF process it is proportional to pressure K into P, K is the proportionality constant. Centrifugal force also because of this rotation of this fluid, centrifugal force will also generated.

So this centrifugal force will be can be given as mr omega square, omega is the omega equal to pi d n okay, d is the diameter, n is the RPM of the magnets. We can we can assume that the this magnets will rotate this fluid will rotate at the same RPM with the magnet. So there is no lag in between this there is no lag in between this RPM of the magnet and RPM of the fluid okay. So what are the indentation force is there.

So centrifugal force will also will act perpendicular to the workpiece surface. So indentation force total indentation force is radial force plus magnetic force plus centrifugal force. This total force will give the indentation to the workpiece surface by the abrasive particles and in case of MRAFF process there is no centrifugal force, only this radial force and magnetic force will act as a indentation force.

Also due to this rotation of this magnet one coriolis force will also generate. This coriolis force can be given as 2m m cross v, omega cross v, 2m omega cross v, m is the mass of this abrasive particle, omega is the rotation of the magnet okay and v is the velocity. So indentation due to the combined effect of magnetic force and centrifugal force, cutting force is also resultant of the tangential force and axial force.

So cutting force is due to the axial force also due to the tangential force. So this resultant of this tangential force and axial force will give the cutting force. So path followed by the active abrasive grains on the workpiece surface is helical. So this path followed by the active abrasive grains on the workpiece surface is helical provides the higher finishing rate than the MRAFF process.

So now in MRAFF process this abrasive particles will traverse along a linear path but in but in case of this R-MRAFF process this abrasive particles will rotate in a circular path, also at the same time you are giving this reciprocating motion so that is why this all the abrasive particles will follow the helical path. So because of this helical path whatever the whatever the area covered by the single abrasive particles is more in case of R-MRAFF process than MRAFF process for the same cycle time okay.

So R-MRAFF process your in R-MRAFF process your abrasive particles will take more path will follow the more path into the workpiece surface. So path followed by the active abrasive grains on the workpiece surface is helical provides high finishing rate than the MRAFF process because it is taking more path.

Uniformly finishes the workpiece like honing operation, so it will like in honing operation you can see this workpiece is kept fixed and this honing tool actually it is reciprocated also at the same time it is rotated. So generate it to generate because of this reciprocating motion and the rotational motion it will generate cross hatch pattern. So this cross hatch pattern this whatever the scratch marks or lay marks by the abrasive particles it will generate the cross hatch pattern because of this cross hatch pattern it helps in oil retention in case of R-MRAFF process.

So here you can see in R-MRAFF process, so this kind of helical motion is given by the abrasive particles. So abrasive particles will move in this helical path. So these are the force diagram here. So indentation force in case of MRAFF process is magnetic force plus radial force and then that is axial force or cutting force is there.

After indentation it this abrasive particle this abrasive particle will cut the surface undulations from the workpiece but in case of R-MRAFF process there are 3 process are there, radial force, magnetic force, and centrifugal force. So here centrifugal force is added here in case of R-MRAFF process. Also there is a one more force which is called coriolis force that is also added in case of R-MRAFF process okay so total force in case of rotational MRAFF process, the total force is axial force this resultant of this axial force and this is the axial force and also this tangential force will give the total cutting force.

So here indentation is due to the combined effect of magnetic and centrifugal force. Cutting force is the resultant of tangential and axial force and path followed by the active abrasive particles on the workpiece surface is helical and provides higher finishing rate than the MRAFF process and uniformly polished the workpiece like in honing operation and generate a cross hatch pattern which helps in oil retention.

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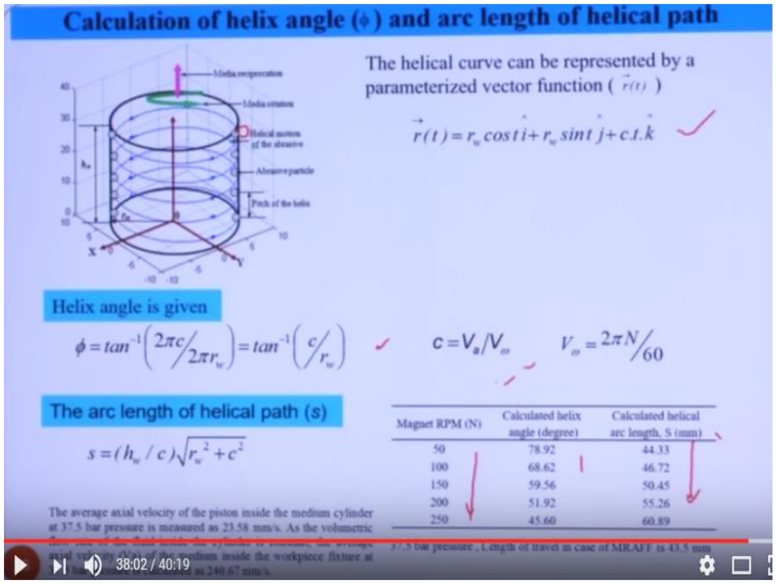

So you can see here this abrasive particles are here at the internal surface of this workpiece this kind of helical path it generates. So what is the equation of this curve is rw so radius of this workpiece cos ti rw sin tij sin t j and c t k. So this is the equation of this helix and what is the helix angle, helix angle is tan inverse 2 pi c by 2 pi r w r tan inverse c by r w and arc length of the helical path, total arc length of the helical path is s equal to hw by c root over r w square plus c square and v here in this helix angle this c is the axial velocity by rotational velocity Va by Vw. So Vw is 2 pi N by 60.

So we can see here with the rotational with the with the increase in the RPM of this magnet from 50 RPM, 100, 150 or 200 and 250 RPM. So helix angle actually helix angle actually it reduces. So helix angle reduces. So if we increase more RPM here increase the RPM here so in that case at certain time okay so helix angle will be parallel to the helix angle will be parallel to the will be parallel okay. So centrifugal calculated helical arc length so if we increase the RPM of this magnet you can see this arc length also increases. Arc length increases means it traverse more path than normal MRAFF process.

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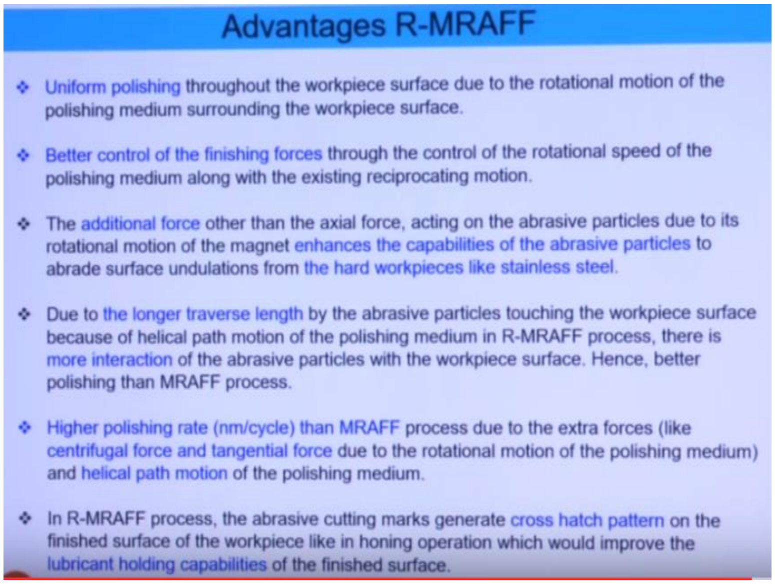

So advantages are of R-MRAFF process uniform polishing throughout the workpiece surface due to the rotational motion of the polishing medium surrounding the workpiece surface. Better control of the finishing forces because we are we have added one more process here which is called centrifugal rotational motion okay so better control of the finishing forces through the control of the rotational speed of the polishing medium along the along with the existing reciprocating motion.

So this additional force other than the axial force acting on the abrasive particles due to its rotational motion of the magnet enhances the capabilities of the abrasive particles to abrade surface undulations from the hard workpiece surface like stainless steel. So due to the longer traverse length so because it is traversing more arc length here in case of R-MRAFF process by the abrasive particles touching the workpiece surface because of helical path motion of the polishing medium in R-MRAFF process there is a more interaction of the abrasive particles because it is taking the more path, more interaction of the abrasive particles with the workpiece surface hence better polishing than MRAFF process.

So higher polishing rate nanometer per cycle than MRAFF process. It has higher polishing rate due to the extra forces like centrifugal force and tangential force due to the rotational motion of the polishing medium and helical path motion of the polishing medium. In R-MRAFF process the abrasive cutting marks generate cross hatch pattern on the finished surface of the workpiece like in honing operation which would improve the lubricant holding capabilities of the finished surface.