Advanced Manufacturing Processes
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Module - 5
Other Advanced Processes
Lecture -5
Application and New Trends in Microwave Material Processing

Welcome to this session on applications of microwave processing of materials, under the course advanced manufacturing processes. In the previous session, we have discussed about the introduction to microwaves, their characteristics, their features and the background of microwave processing of materials, how the microwaves interact with different types of materials like reflecting materials, absorbing materials and transparent materials.

In this session, let us move ahead with some more applications of microwave in material processing like as I have already indicated in the previous session, microwaves can be used for heating purposes; microwaves can be used for enhancing the chemical reactions; microwaves can be used for curing of polymers and so on. Now, let us look at these with some more details particularly putting more emphasis on engineering applications like metallurgical applications in sintering, in joining cladding and so on.

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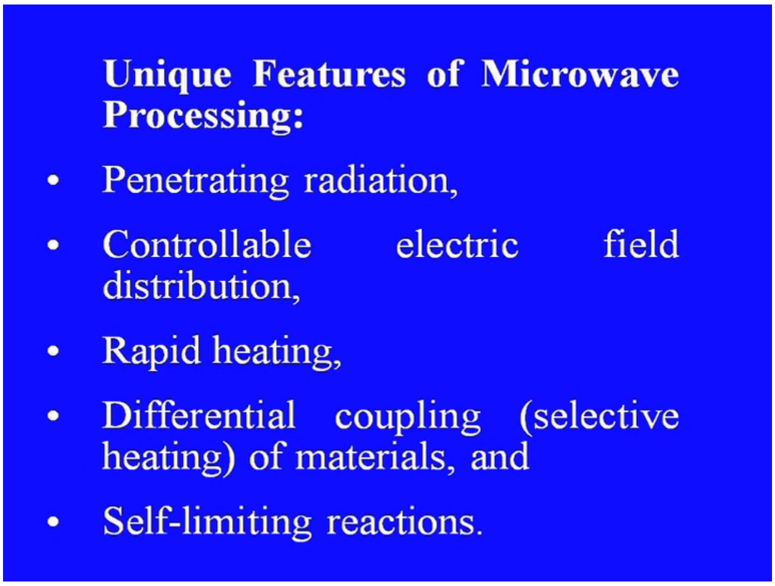

Let us brush up the unique features of microwave processing, we have already indicated in the previous discussion. The first and foremost feature of the microwave processing is penetrating radiation, unlike the conventional heating in which the heat waves move from outside, outside the surface of the body or the object to be heated up or the processed. In case of microwave, it penetrates throughout the volume or it gets reflected as in the case of reflecting materials or reflecting mirrors. In that case no processing is possible; processing is possible only when the material is absorbing and it penetrates throughout the volume of the material. This is one of the important features of microwave processing.

Then second is controllable electric field distribution. This also I have already indicated we can have better control as far as the electrical field is concerned. Since we need to apply one electric field at a particular frequency; we can have better control of this electrical field and the power absorption as I have already indicated in the previous discussion itself.

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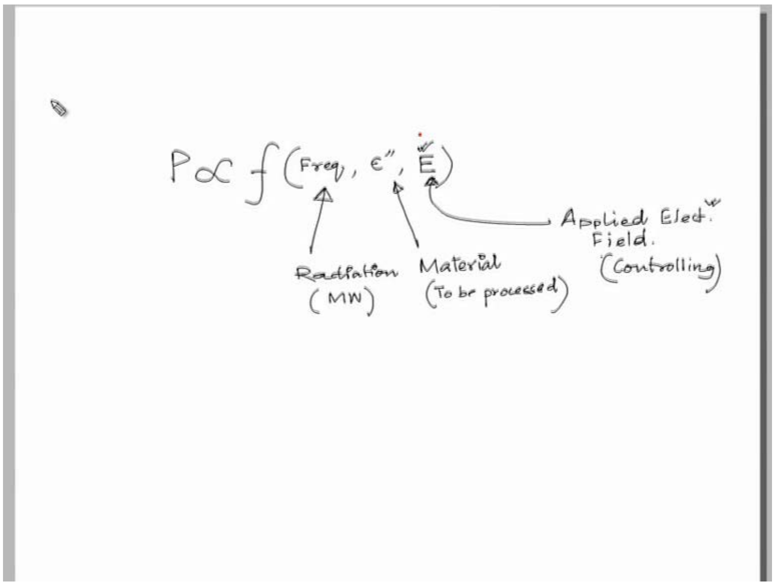

Power absorption say p is a function of, is a function of frequency of the applied microwave. Then the dielectric losses of the material - so this is material, and electric field applied. So, this is regarding the radiation, radiation or the microwave frequency or the microwave. We can say, so this is regarding the material to be processed, say this is to be processed and this factor is nothing but the applied electrical field, electrical field. So, this is this gives us flexibility for controlling. So, therefore, the power that will be dissipated or absorbed in microwave, so will be influenced by this electrical field - this E.

Now as we know all of us know as far as the control of the process is concerned. So far as the quantity is electrical quantity; it is easier for us to control the process. So, it is the case which microwave processing of materials. Then another feature is very rapid heating. As we know microwaves travel in the speed of light. So, therefore, so penetration is taking no time as far as the realistic products volumes are concerned. And if the material is absorbing material, then the interaction becomes very fast and the heating becomes very fast. Then another important and very, very significant feature of this processing is the differential coupling; that means, the selective heating. This, what is the meaning of selective heating. So, this is this can be explained like this.

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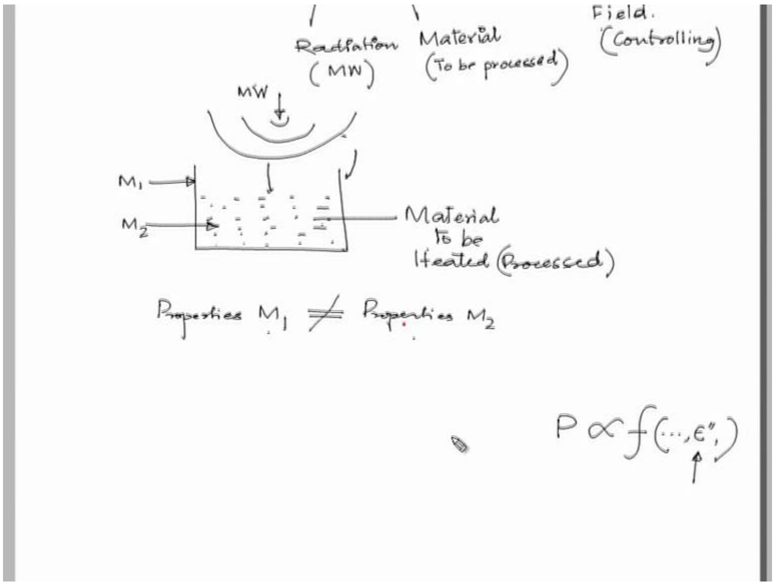

Suppose there are two materials. In this and this is exposed to microwave. And this is material to be heated or we can say processed. Now microwave are falling on this material as well as on this material; that means, both the materials we are exposing to microwaves. But the significant thing is that depending on the properties of these two materials, so this is one material say M 1 and this is another material m two. However, the properties of M 1 are not equal to the properties of M 2. Therefore, as we have already seen, the heating is a function of, heating is a function of one among other factors dielectric loss; this is a material dependent factor as I have already indicated. And since these properties are not equal, therefore the effect of the heating on these two materials will be different.

Rather we can understand this in this way, both the materials will not get affected in the similar fashion by the incident microwave energy. In other words, the materials will get heated up in a different way. This is the very recent why while heating, some materials say cup of water inside the microwave oven, we can hold the cup very comfortably even though the inside material is very hot; that means, water is getting heated faster rather than the material that contains water.

Of course, if the container also a microwave absorbing material then it will be a different case, then the container will also get heated up. Therefore, I would request not to experiment this without knowing the material properties inside home microwave ovens. One need to know which are the microwave's friendly materials or which are the microwaveable materials; that means, they do not get heated up while expose to microwaves and microwaves.

So, please be careful while experimenting with yourself rather do not go for it until and unless you have sufficient information on this. One material may be very hot, one may be at room temperature or both may be very hot. For that matter it is not the question of one or two materials, whereas we can keep number of materials together, but the heating on these materials will takes place according to their own materials properties. And therefore, the degree of heating in those materials will be according to material properties. This is called selective heating or differential coupling.

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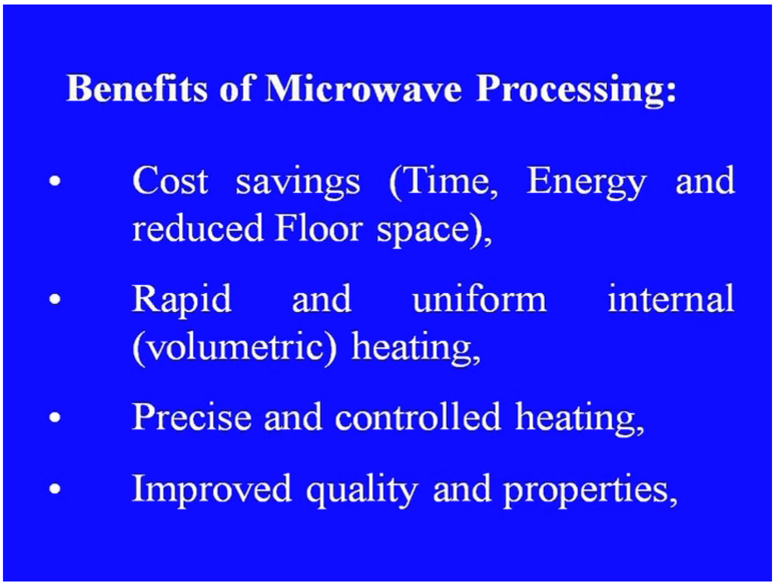

Now, let us quickly look at the benefits of microwave processing as well very quickly. As we have already indicated, cost saving; this is one of the important aspects of microwave material processing. This cost earning we can derive in terms of time saving; time saving is nothing time is nothing, but cost and with the saving and of course, deduced floor space. Because in a very limited space, we can have very high energy output in terms of electromagnetic radiations or microwaves.

Then the microwaves can have rapid and uniform internal heating, this we have already discussed in details. How uniform heating can takes place while exposing to microwaves. Then precise and control heating, then improved quality and properties this terms are also discussed already. Then another features is their environment friendly and clean process, unlike some other conventional heating process heating furnaces etcetera, where conventional heating or burning of some fuels may be required of course, in induct induction heating it is not required. And then potentially to process materials or products that are different or impossible to produce reliably by conventional methods. So, this microwave processing may work better in those cases.

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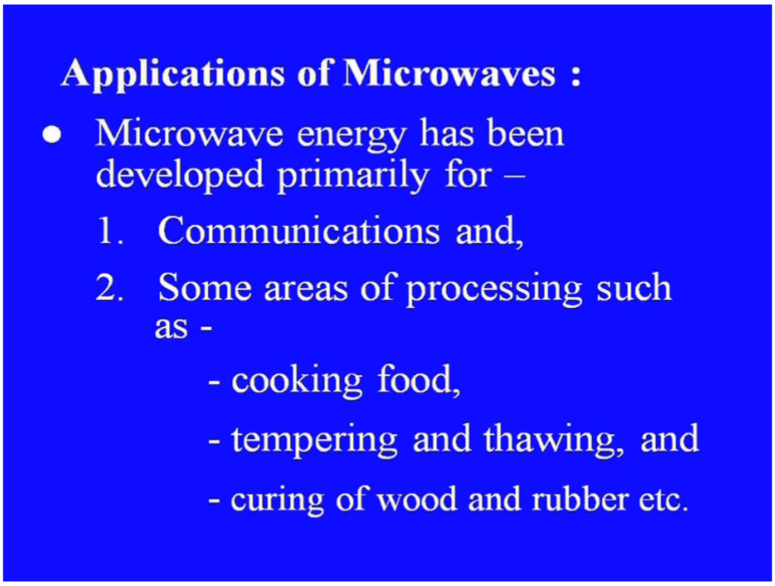

Now, let us come to the applications of microwaves. In material processing, the application of microwave are not very popular, particularly for engineering material processing. It has been popular for food processing. But if we look at the history of microwaves, they were basically developed for communication purposes and still they are going strong in almost all communication equipment used microwaves extensively. Even the mobile communication, satellite communication people they use microwave very extensively. Then another reason for which this microwaves were developed in the early years were food processing or cooking food, then tempering and thawing then curing of wood and rubber etcetera. These were some of the earlier applications of microwaves.

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However, application of microwave energy has now been extended to many other areas. This includes number one sintering of ceramics, composites and metals. Then joining of ceramics, composites, and metals; then controlled nucleation and crystal growth. Then number four drying and synthesis of materials. As I have already indicated, there need not be heating always associated with microwave processing, but could be synthesised as far as the reactions are concerned chemical reactions are concerned or curing of polymeric composites are concerned or some deriving some chemicals new chemicals to the synthesis. This microwave exposer can be very, very useful tool.

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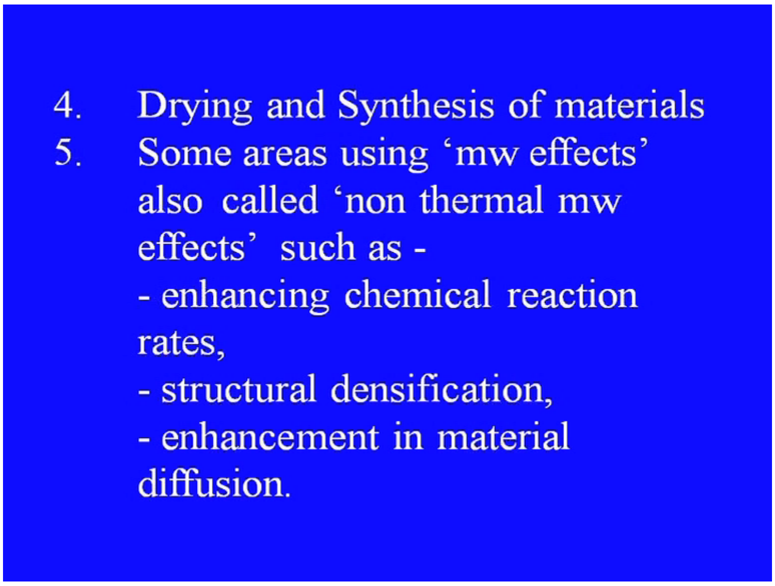

Then some various using microwave effects also called non-thermal microwave effects. Such as enhancing chemical reaction rates then structural densification, enhancement in material diffusion this microwaves can be used. These are some of the aspects even today scientists are yet to offer some acceptable explanation regarding what happens or the mechanism, how it happens. People have seen or scientist have seen the effect of microwave radiation on some chemical reaction is taking place or enhancing the reaction rate etcetera. But unable to correlate with some known facts or known phenomena. So, this we call at this moment we call microwave effect may be with further research within few years, this things will be able to be explained.

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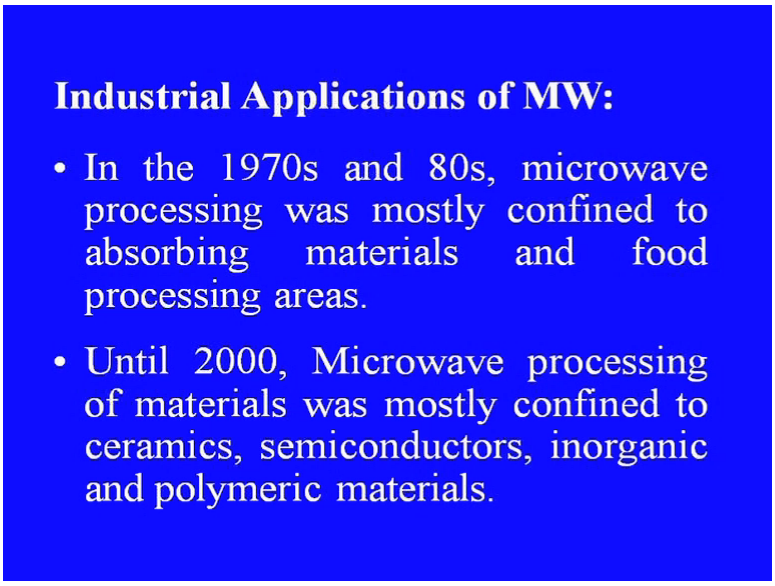

Now, let us see some industrial applications of microwaves. In the 1970s and 80s, microwave processing was confined to absorbing materials and food processing areas. Until the year 2000, microwave processing of materials was mostly confined to ceramics, semiconductors, inorganic and polymeric materials.

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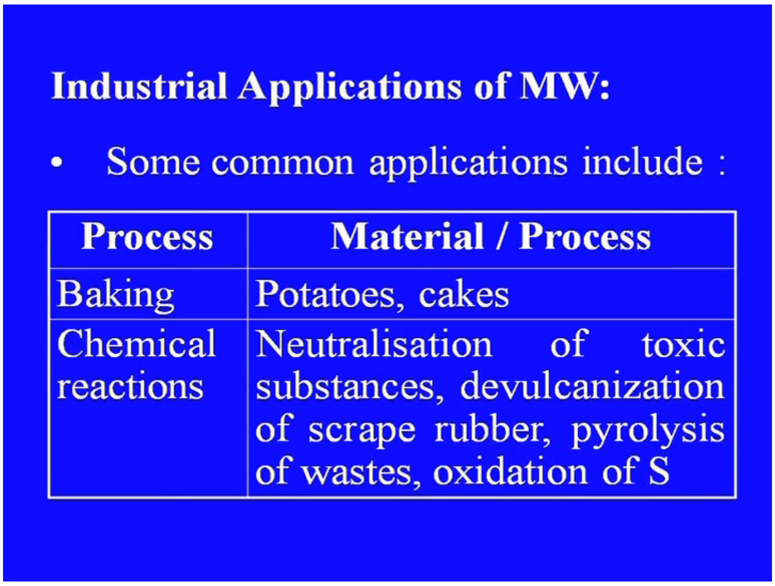

Now there are different other areas where microwaves are being very widely used some of the common applications include this are say for food processing baking, so baking of potatoes, cakes and so, on. So, are cooking of foods common food items, this is very common applications of microwaves. Then for chemical reactions to initiate or to complete, this microwave exposer is being used say for example, neutralisation of toxic substances, devulcanization of scrape rubber, pyrolysis of wastes, oxidation of sulphur and so on. So, in cooking, cooking of food grains, vegetable, meat, fish and so on is very useful or very effective.

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Process	Material / Process
Cooking	Food grains, vegetables, meat
Curing / Hardening	PVC, PUF, Epoxy resin, Polyester, Plaster of paris, cement, cellulosic membranes, wood gluing with adhesive, epoxy laminates, backellite etc.

Then another very useful application of microwave is like curing or hardening of polymeric composites polymeric materials. This polymeric materials include polyvinyl chloride or PVC in short, polyurethane foam like PUF, what we call then epoxy resin polyester plaster of paris cement, cellulosic membranes, wood gluing with adhesive, then epoxy laminates, Bakelite and so on.

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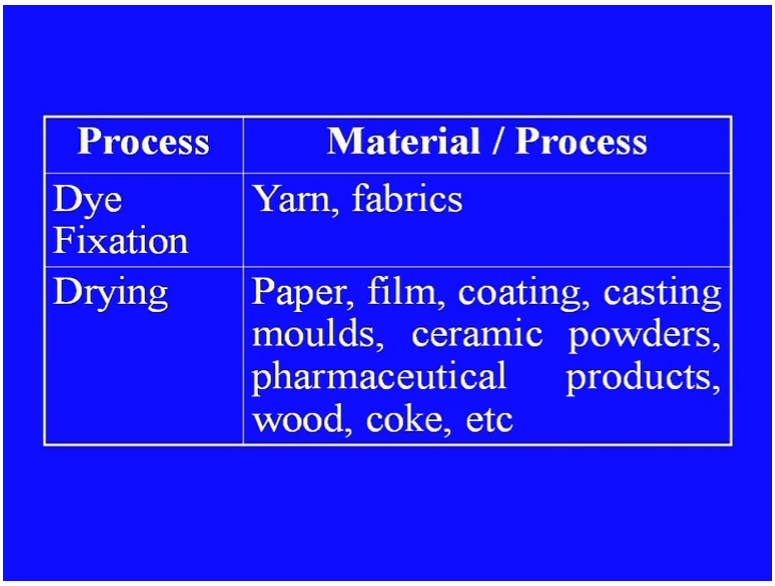

Process	Material / Process
Dye Fixation	Yarn, fabrics
Drying	Paper, film, coating, casting moulds, ceramic powders, pharmaceutical products, wood, coke, etc

Then for dye fixation, the microwaves can be used for yarn or fabrics. Then for drying, say drying of paper, film, coating, casting moulds, ceramic powders, pharmaceutical products, wood, coke and so on.

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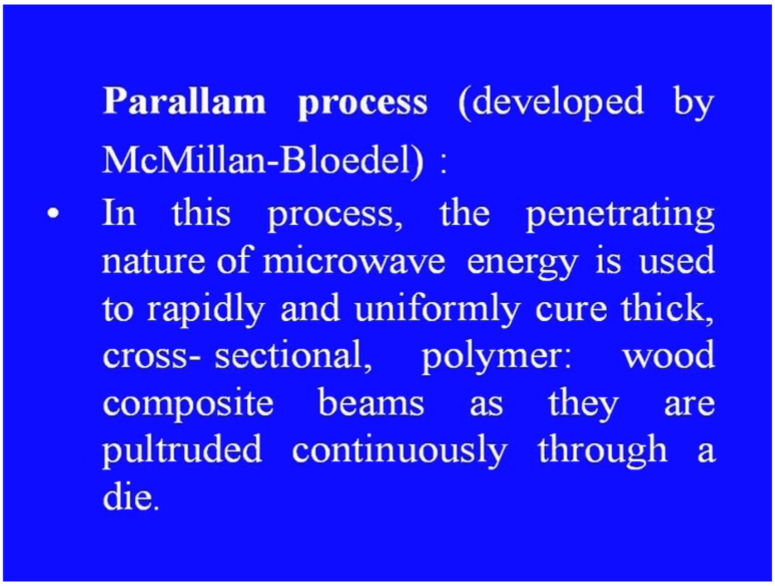

Then there is one process have been this has been developed by McMillan-Bloedel. So, in this process, this process is called parallam process. In this process, the penetrating nature of microwave energy is used to rapidly and uniformly cure thick, cross-sectional, polymer: wood composite beams as they are pultruded continuously through a die. As most of us know the pultrusion process which is mostly used for processing of polymers or polymeric composites, basically for polymeric composites pultrusion is a process. So, in this process along with this pultrusion, we can use microwave energy where the material will get cured almost simultaneously.

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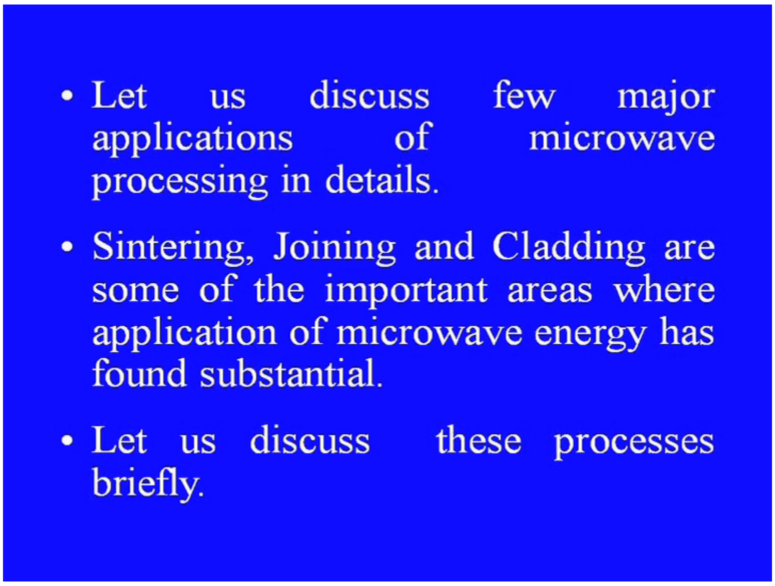

Now, let us discuss few major application of microwave processing in details. This processes includes sintering, joining and cladding which are very important areas where application of microwave energy has been found to be substantial. Let us discuss some of this processes briefly.

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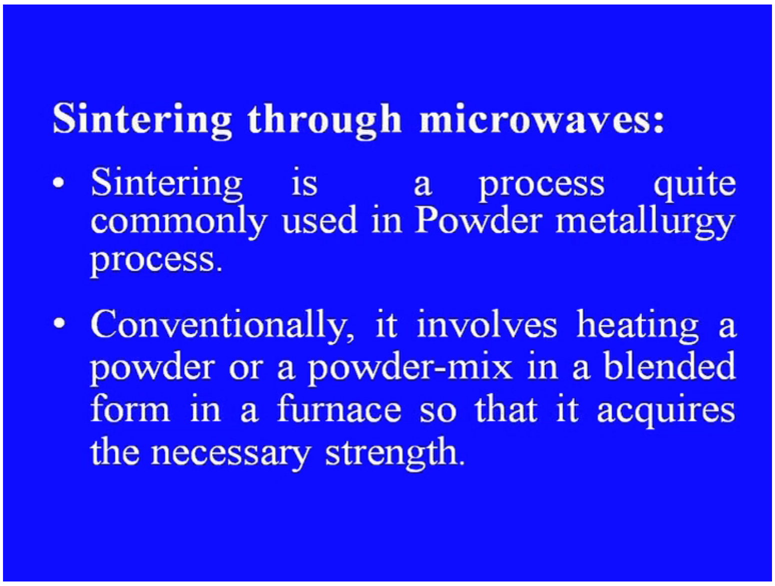

Let us first take sintering using microwaves. As we know sintering is a process quite commonly used in powder metallurgy process. Conventionally, it involves heating a powder or a powder-mix in a blended form in a furnace, so that it acquires the necessary strength. Tinga and Vas, these are the two scientist; they first reported the use of microwave for the sintering of ceramics in the year be back 1968. Consequently, there are after several researchers continued for concentring using microwaves.

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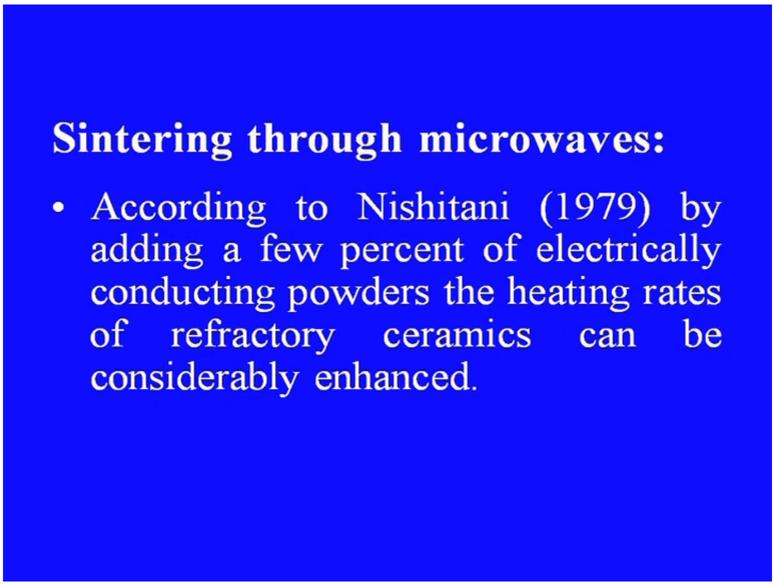

Another scientist called Nishitani in the year 1979, he has founded by adding a few percent of electrically conducting powders the heating rates of refractory ceramics can be considerably enhanced. In the last session itself we have discussed ceramics are transparent materials as far as the microwave energy is concerned. However, as we have indicated, if we mix some materials which are microwave absorbing materials into this ceramics then the heating rates can be enhanced. Those absorbing materials will be responsible for absorbing the microwaves and then that heat will try to heat the ceramics initially which will make ultimately the ceramics also as an absorbing material at higher temperature.

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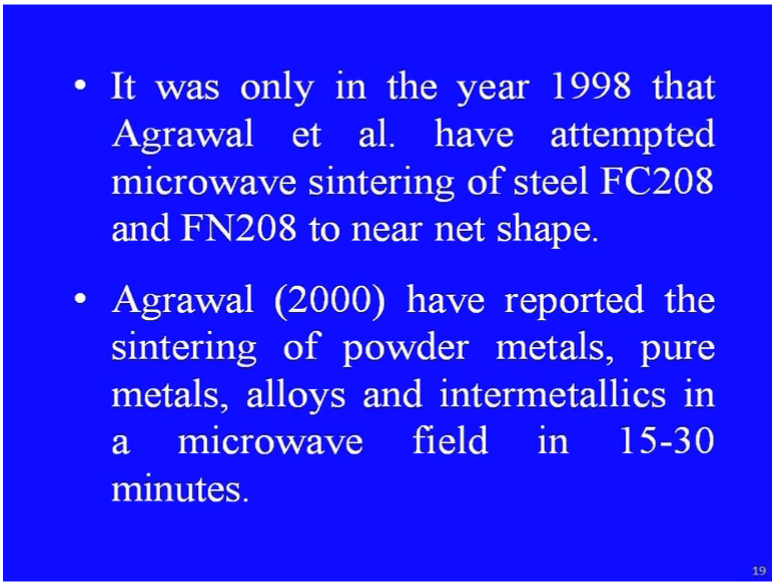

It was only in the year 1998 that Dennis Agrawal, Professor Dennis Agarwal and his co-researches have attempted to microwave sintering of metal steels FC 208, and FN 208 to near net shape. In the year 2000, Agarwal have and his co-researchers have reported the sintering of powder metals, pure metals, alloys and intermetallics in a microwave field in 15 to 30 minutes.

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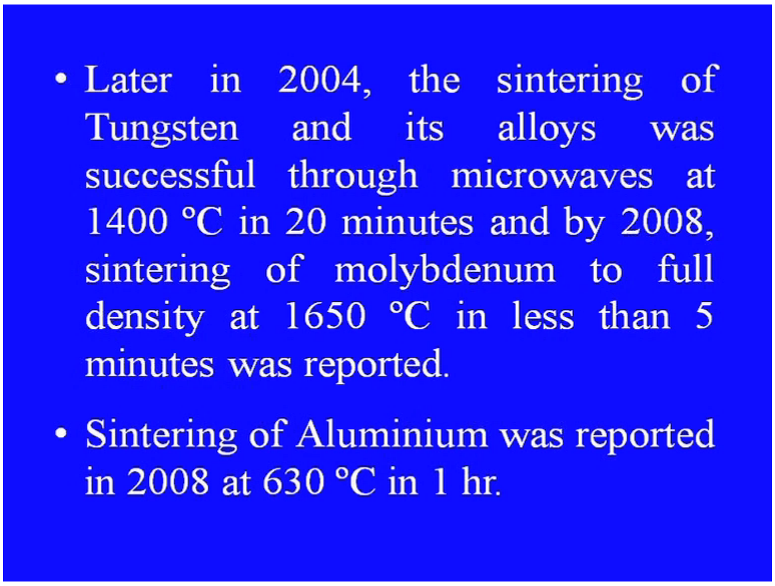

Later in the year 2004, the sintering of tungsten and its alloys was successful through microwaves at 1400 degree Celsius in 20 minutes. And by the year 2008, sintering of molybdenum to full density at the temperature of 650 degree Celsius was achieved in less than five minutes. Then sintering of aluminium was also reported in the year 2008 at 630 degree Celsius in one-hour duration.

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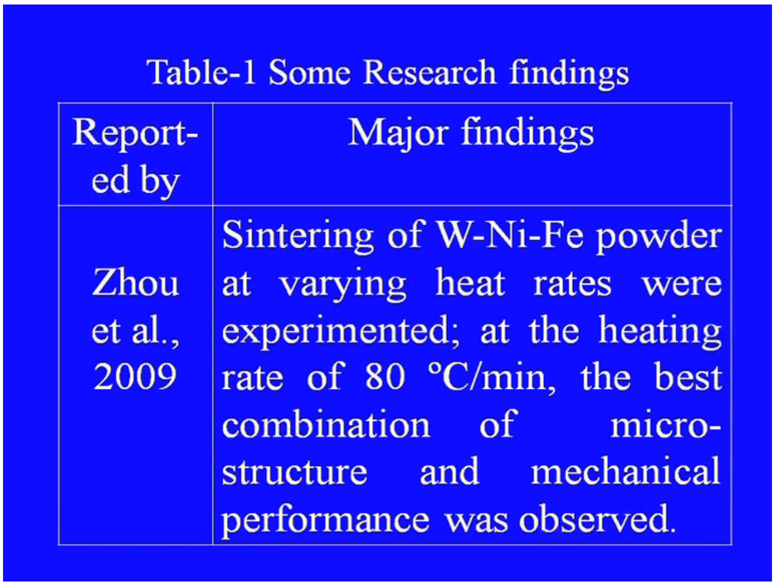

Let us see some more research findings as far as the sintering is concerned. One work was reported by Zhou and his co-researchers in the year 2009, they worked on sintering of tungsten, nickel and iron powder at varying heat rates, and heating rate of 80 degree per minute. They have found to be the best for microstructure and mechanical performance.

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Table-1 Some Research findings

Mondal et al., 2008	Attempted sintering of premixed and pre-alloyed 90W-7Ni-3Cu through microwave and conventional way; results showed higher density, micro-hardness and fine microstructures without micro cracks.

Then another group of scientist like Mondal and his co-researchers in the year 2008, attempted sintering of premixed and pre-alloyed 90 tungsten, 7 nickel and 3 copper powder through microwave and conventional way. They have found that higher density higher micro hardness and fine microstructures without any micro cracks for this microwave sintered products.

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Padma-vati et al. 2008	Carried out sintering of (316L) and ferritic (434L) S.S. through conventional and microwave mode with upto 1.5 % graphite addition. They reported higher corrosion resistance and improved corrosion properties.

Then Padmavati and his research group carried out sintering of 316L stainless steel and ferritic stainless steel - that is 434L through conventional and microwave mode of heating with 1.5 percent graphite addition. They have found at higher corrosion resistance and improved corrosion properties with this microwave sintered products. The again Padmavati and his group reported in the year 2008, sintering of aluminium, magnesium, and solder alloys the tensile testing of this sintered products showed better properties in the microwave-sintered conditions, then the conventionally sintered ones.

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Rajkumar and Arvindan, 2009	Copper-graphite composites were prepared using microwave hybrid heating without any cracks.
Chillar P. et al., 2008	Sintering of Mo powder was done through microwave radiation with 98% Theoritical Density.

Then another group Rajkumar and Arvindan in the year 2009, they have reported about copper graphite composites by heating in a hybrid mode. And they have found there is no crack in the composites while (( )). So, then another group Chillar and his co-researchers, they have sintered molybdenum powder, and they could achieve 98 percent of the theoretical density in this sintered products which is quite substantial.

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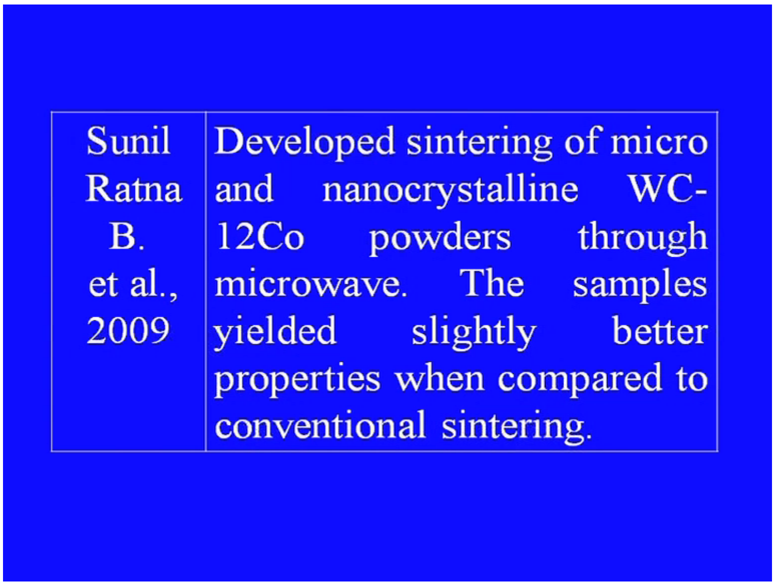

Then Sunil Ratna and his co-researchers developed sintering of micro and nano-crystalline tungsten carbide and 12 cobalt powders through microwave. They have found at the samples of microwave-sintered samples in the slightly better properties when compared to the conventionally sintered products of the same material.

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Now, let us move onto another application of this microwave processing of materials, which is mostly the engineering application - that is microwave joining of non-metallic materials. Trans welding institute successfully used the modified microwave multimode cavity for welding of polymers. They carried out this welding of the polymers using microwave energy at 2.45 giga hertz of frequency. They have designed applicator to be capable of irradiating the entire component and produce complex 3-D joints, which was considered to be difficult ones as far as the other techniques are concerned. But the encouraging factor is that the welds where created in less than one minute which is quite substantial.

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Then microwave heating has been extensively used for joining of ceramics and ceramic composites as well there have been lot of work reported in the recent literature. Ifthikar Ahmed and his co-researchers in the year 1997, could join silicon carbide ceramics and composites using polymer precursor at 1000 degree Celsius in one to one and half hour of duration. Then Ifthikar Ahmed and alleys they have reported in the year 2001 about this microwave joining of 48 percent alumina, 32 percent zirconia, and 20 percent silica ceramics. And they have found that it heals higher joins strength and the best metal even best metal even. Then (( )) and black, they have also reported joining of alumina and alumina ceramics using commercial scaling ceiling glass in between the two materials that is also called the inter layer and they have reported in it the year 2001.

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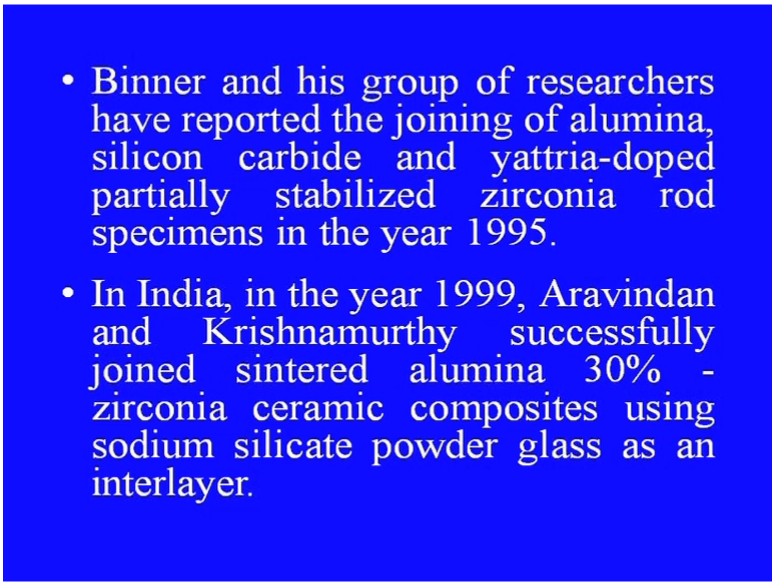

Then Binner and his group of researchers have reported the joining of alumina, silicon carbide and yattria-doped partially stabilized zirconia rod in the year 1995. In India, in the year 1999, Arvindan and Krishnamurthy successfully joined sintered alumina 30 percent and zirconia ceramics using sodium silicate powder glass as an inter layer. Then another important development in this microwave joining is microwave joining of bulk metals. In spite of significant progress there has hardly any detailed report on microwave joining of metallic materials. The main reason was due to the misconception, which was removed recently that all the metals reflect microwaves and cause plasma formation. So, this was also explained last session.

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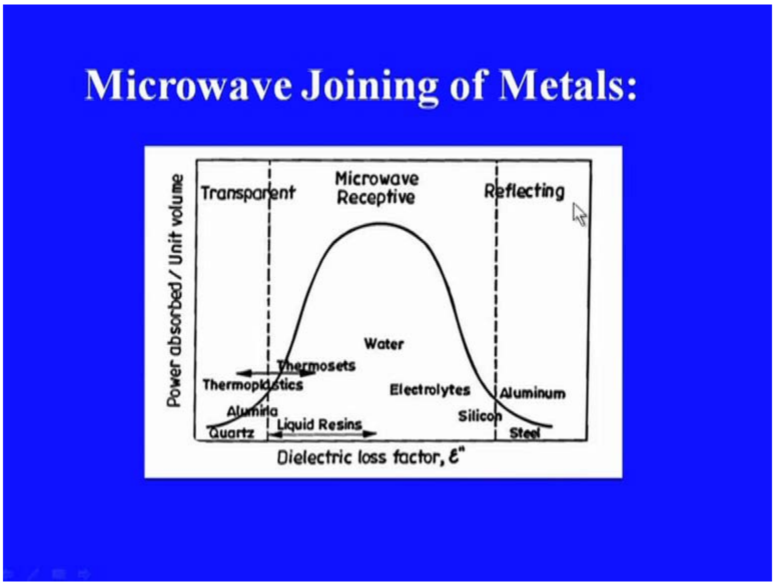

As this curve is shown in the screen you can see. So, this the power absorbed per unit volume of the materials. So, this is very high for water and low for materials like alumina, thermo sets, thermoplastics etcetera. This alumina is nothing but a ceramic, and also it is low for the materials like aluminium, copper, silicon, steel and so on. These are materials and they are considered to be the reflecting materials whereas, the other extremes materials like the ceramics etcetera are considered to be transparent materials. Only these materials like water etcetera, they absorb material with high degree of absorption. Thus this metallic materials to be processed with or using microwave is a challenging task.

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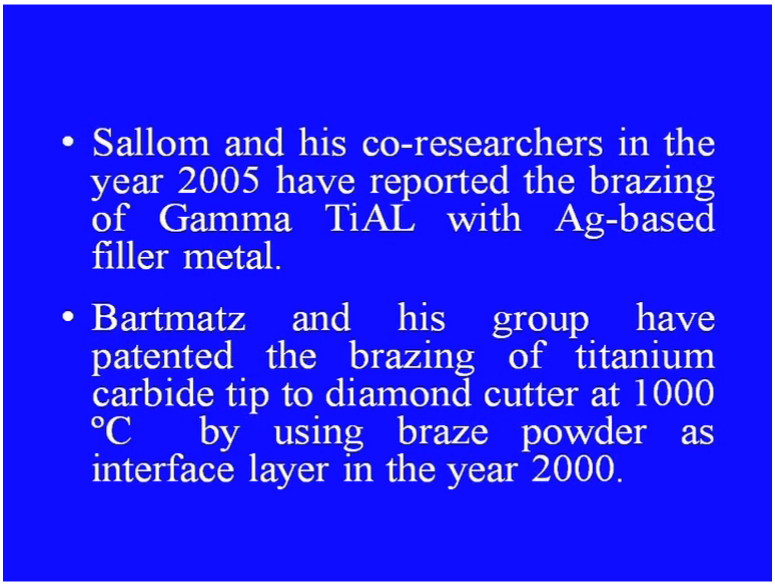

Sallom and his co-researchers in the year 2005 have reported the brazing of gamma titanium aluminium and silver based filler metal. Bartmatz and his group have patented the brazing of titanium carbide t to diamond cutter at 1000 degree celsius by using braze powder as interface layer in the year 2000. (( )) and (( )) in the year 1995 have reported the joining of thin steel specimen in the range of 0.1 to 0.3 millimetre in an inert atmosphere. Then again Agarwal and his group in the year 2006 have reported the joining of regular steel and the cast iron in a microwave field using some brass alloy in two to three minutes.

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Then let us come to some of the developments in microwave joining of bulk metals and this developments have taken place in IIT, Roorkee itself, in the microwave material processing lab. This has been reported for the first time by the IIT, Roorkee research group, in which fortunately I am also a member of the group. The microwave joining of bulk copper has been carried out, microwave joining of steels have been carried out, microwave joining of steel to mild steel has been stainless steel to mild steel have been carried out and so on.

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This is in the screen some specimens are being shown. So, this are these are the plates of copper and they are been joined using microwave radiation in this we can see some of the specimens being joined by microwaves using this stainless steel materials. So, these are stainless steel plates they are being joined here these are 316 stainless steel. So, they are being joined in microwave processing laboratory by using 2.45 giga hertz microwave.

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So, this is the joint zone we can see joint zone. So, this is this is the base material and this the base material it is a stainless steel. So, in between the researchers have used some powder layered in that is also called inter layer which is called inter layer in between. So, this thickness in between this will be something around 50 micron in between; that means, this interlayer between these two materials are very, very thin.

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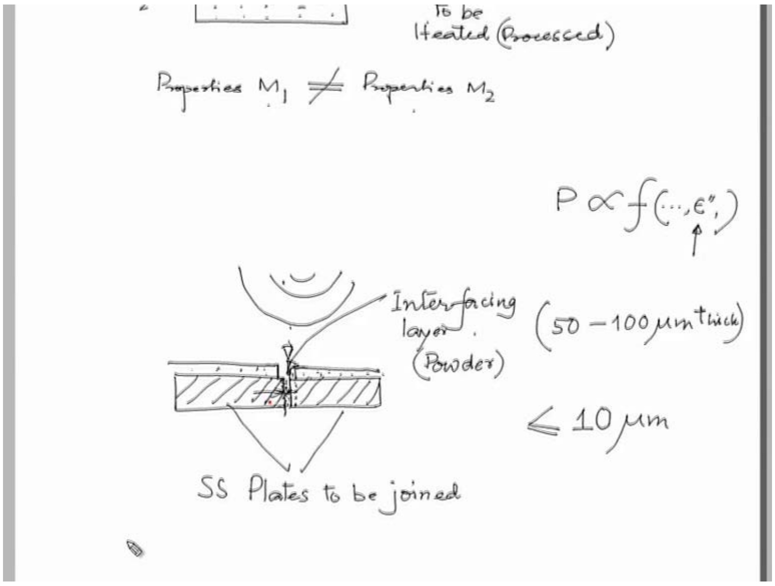

So, this can be explained like this. This is one of the plate, say this is a stainless steel plate then another plate is like this; they need to be joined. So, this is also another plate. So, we can say these are the plates to be joined say SS plates - stainless steel plates. In between, in between we are keeping one interfacing layer; this is called interfacing layer. So, this is nothing but a powder layer, then this material will be covered, this material will be covered by some other material. So that while exposing to microwave this metallic surfaces do not reflect the microwaves and cause harm to the equipment, and the microwaves would will fall only to this layer. And therefore, this layer will get heated up they will get melted then the very nearby to this powder layer will get melted and there will be a bond formation between them.

This distance I am talking about that gets melted of the parent material will be something around ten micrometre only. So, something less than or equal to ten micrometer only, and this interfacing layer, so this will be something around 50 to 100 micrometre thick; that means, we can think about how thin this layer is and how thin this heat effected zone or the melted zone of the original material is that shows the preciseness of this technique and the usefulness of this technique.

This figure, so this is the layer in between the powder layer which got melted during heating, and then on cooling they got the structure something like this. Whereas, this we can see the relatively different micro structure these are the base materials or the parent materials which are been joined like this. And upon comparison with thick welding, we have found to be these joints almost to be equivalent as per as the strength is concerned. However, in some cases bending strength is found to be less than the thick counter parts or the thick joints. But in most of the cases the elongation is more and significant thing is that the porosity in this joint porosity is very very less.

As we know porosity is nothing but, they are pockets of defects. But in this cases, the porosity is something close to one percent only or less than one percent. Whereas, in case of thick welding etcetera we have seen porosity can be four percent, three percent, five percent and so on and higher the porosity, we would say inferior is the joint which we have found in case of microwave joining to be very good.

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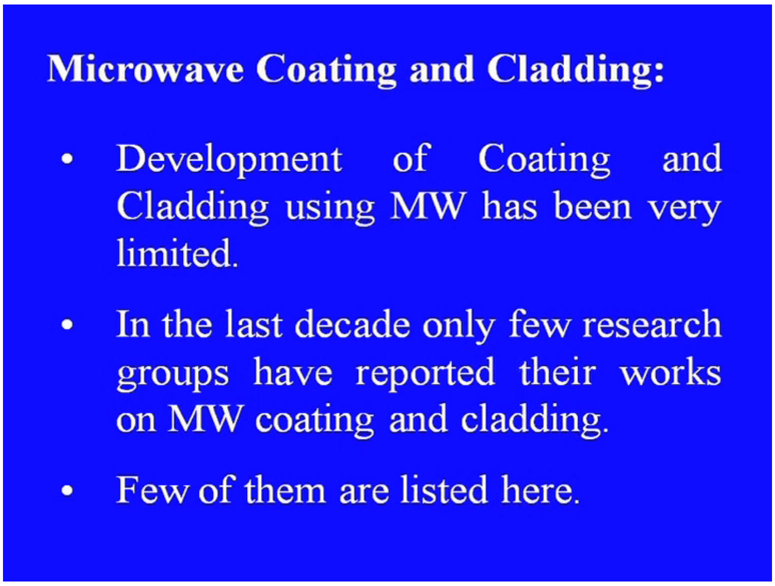

Next comes another application which is emerging application, not this techniques are very recent developments and say only one year or two year old only. And they are yet to come to the industries to be adopted, but we are confident that this will come very soon to the industries as well. And this technique is also been developed in the IIT, Roorkee laboratory and so that have been claimed for both microwave joining of bulk metals and microwave cladding of metallic materials as well. The development of coating and cladding using microwave have been very limited globally. In the last decade only few resource groups have reported their works on microwave coating as well as in cladding.

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Reported by	Developments
Das et al. 2008	Coating was experimented with Microwave exposures for 60 mins. and 90 mins.. Porous, thin coating (~ 42 μm) and dense, thick coating (~ 661 μm) of aluminum oxide on aluminum substrate could be developed.

Only few of them are listed here, very notable few. One work is reported by Das and his co researchers in the year 2008. So, they have reported about coating with microwave exposures for 60 minutes and 90 minutes, which is quite high considered to be quite high. And they have obtained porous coating something around 42 micron thick and dense and thick coating something around 0.6 mm thick of aluminium oxide on aluminium substrate. Then another work being reported by Kamarota and his co-researchers. So, they have eradiated titanium substrate with nickel aluminium coatings, to obtain nickel aluminium coating and they could obtain good results on titanium substrate.

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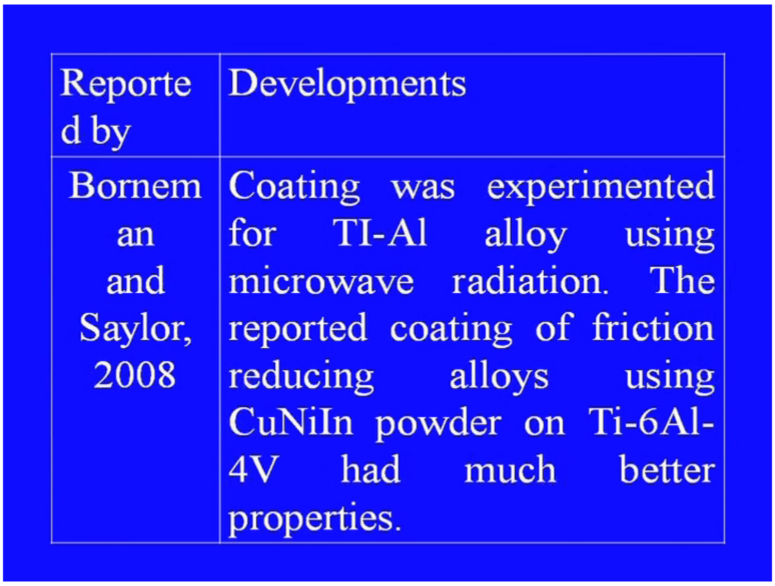

Reported by	Developments
Borneman and Saylor, 2008	Coating was experimented for TI-Al alloy using microwave radiation. The reported coating of friction reducing alloys using CuNiIn powder on Ti-6Al-4V had much better properties.

Another group Borneman and Saylor. So, they have successfully developed coating for titanium and aluminium alloy using microwave radiation. They have reported the coating of friction reducing alloys using copper, nickel, indium powder on titanium six aluminium and four vanadium alloy. And they have found better properties of microwave induced coatings. Then some recent development in microwave cladding on metallic substrates, so after some trails it was found that this possible develop metallic coating with substantial thickness on metallic substrates through novel processing technique known as microwave hybridity.

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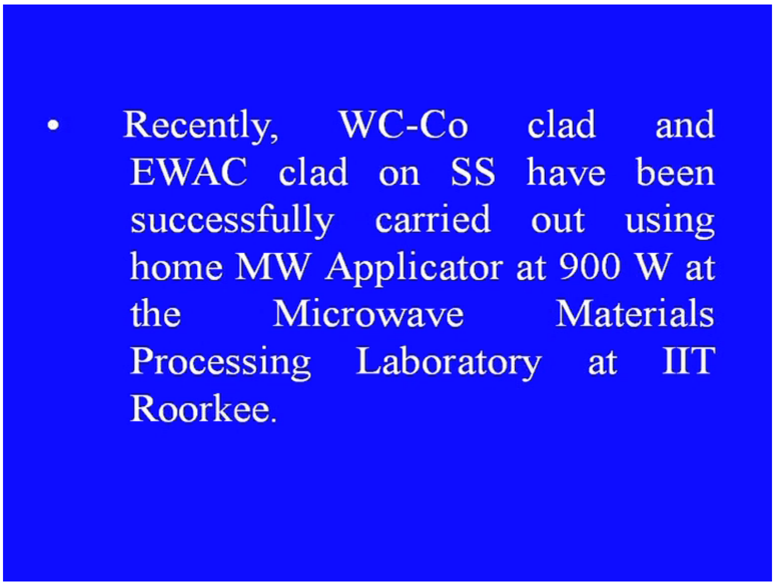

Recently, tungsten carbide and cobalt clad and EWAC clad on stainless steel have been successfully carried out using home microwave applicator at 900 watt on using 2.45 giga hertz microwaves and this was being carried out in the microwave material processing laboratory at IIT, Roorkee.

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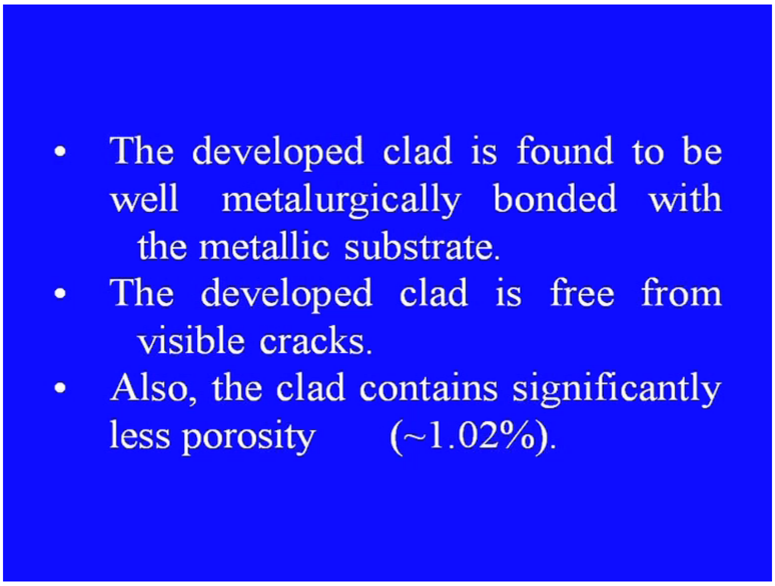

The developed clad is found to be well metallurgically bonded with the metallic substrate. The clad is free from any visible cracks, and also the clad contains significantly less porosity which is almost one percent and which is substantially less.

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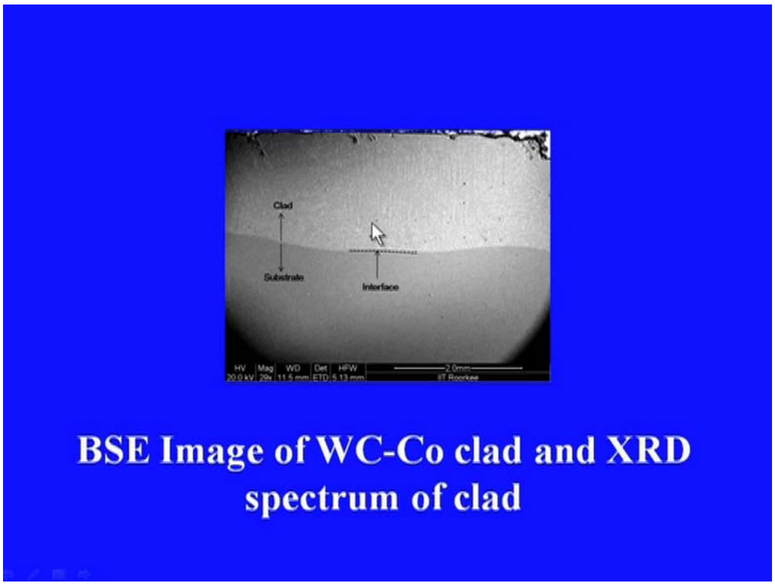

So, this an image of clad, so being developed. So, this is the image of tungsten carbide and cobalt clad. So, this is the substrate we can see in this screen. This is the substrate that is stainless steel substrate and this is the clad. So, we can see a very homogeneous micro structure of this clad, and there is no visible crack, no visible porosity; that means, very uniform cladding without much have defect and this was being produced in the microwave applicator of only 900 watt capability at 2.45 giga hertz. And this was of course, fabricated in less than 10 minutes of duration. As we know tungsten carbide is one of the very strong materials and very high the temperature the melting point high melting point materials. And this is a very good material as far the wear resistance is concerned. So, therefore, tungsten carbide cobalt material combination as a cladding material is very good as for as the industrial applications is concerned and that could be developed using microwave energy.

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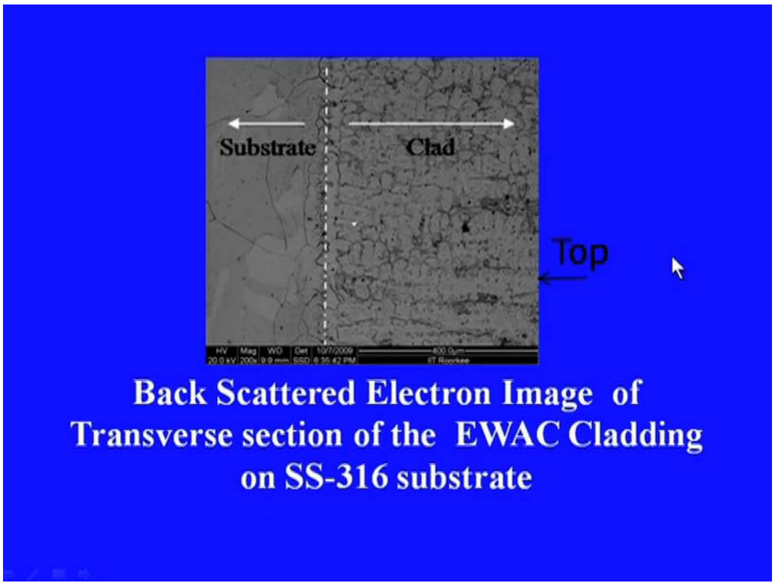

So, this is the cross section wise how the clad looks like. So, we can see this is the substrate that is a stainless steel substrate, and this is the clad material. And we can see there is a very smooth transition of this joint; that means, the cladding; that means, the metallurgical bonding has taken place between the substrate. And the clad material there is no mechanical bonding sort of things that exists in case of coating, and that is how they become little weak, but here it appears to be as a integral part of this substrate material itself. Although there will be little property difference between them as that the cladding material is different. So, this is the EWAC material and this is the stainless steel material and EWAC is also known for very good wear resistant material, and therefore, EWAC material claded on stainless steel could be a very good industrial solution as far as this is cladding is concerned.

Now let us summarize what we have discussed in this session, we have discussed the advancements in microwave processing various applications of microwave processing. And then in particular, sintering, joining, joining of ceramics, joining of bulk metallic materials and then cladding of different materials on bulk metallic substrates using microwave energy. We have discussed and these are very, very significant applications of this microwave material processing in the years to come. We hope this session was informative and interesting.

Thank you.