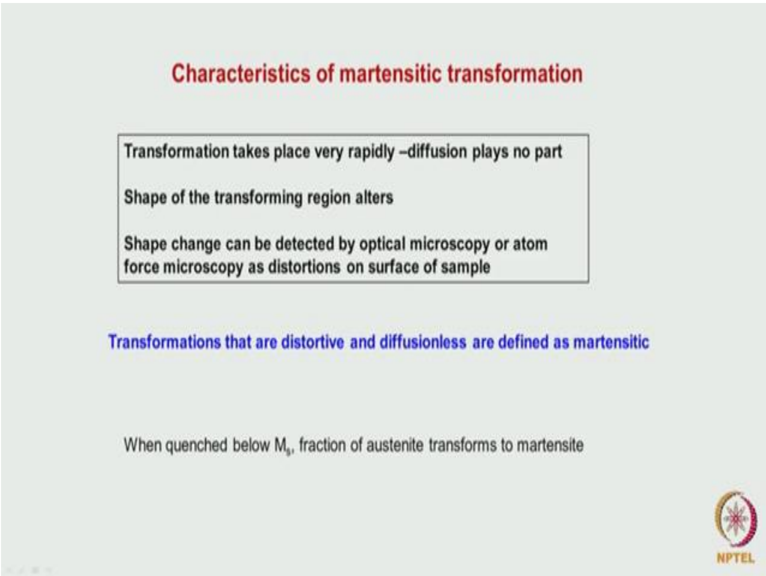
Defects in Materials

Prof. M Sundararaman
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture - 31
Martensitic Transformation – 1

Welcome you all to this course on Defects in Material. Seeing the title, you will be thinking why this transformation in materials is being taught in this, defects in material course. Because martensitic transformation has got lot of characteristics which are quite similar to twinning, that is why this transformation has been included as part of defects in material. Especially the crystallography of the phase transformation is quite similar to twinning deformation or homogeneous deformation.

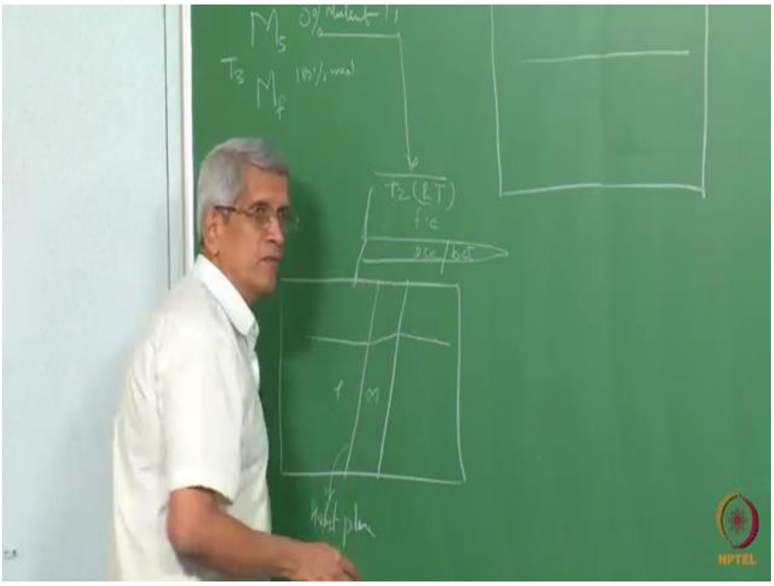
(Refer Slide Time: 00:52)



Before we go further let us look at what all the characteristics of the martensitic transformation. The first thing which one should understand that this is a very important transformation which occurs in the material and this is the transformation through which the low carbon steels are most of the iron carbon steels could be hardened. There are various ways in which like there are like maraging steels there are many types of steels are there are many steels which are ferritic martensitic steels all of them imply martensitic transformations to change the mechanical property of the material.

The first thing about martensitic transformation why let us first look at some of the characteristics and observations before we go into the crystallography. The first thing which had been seen is that.

(Refer Slide Time: 01:47)



If you take a sample keep it at a very high temperature T 1, and then quench it to a temperature T 2 which is maybe room temperature. Then the rate at which it is being quenched at this may be around 10 to power of 3 or 10 to power of 4 degrees centigrade per minute per or second you can take it. Then what we are seeing it essentially is that when this quenching is very fast, it undergoes a transformation especially in an from FCC to BCC. And what is essentially important is that when the sample is being seen, some new phase which has formed the grain which looks like a needle or a plate shaped. And the size of the plate is so large that within very short time if it is by diffusion this plate has to grow it is almost impossible; that means, that this transformation essentially appears to be a diffusion less or diffusion does not play any part.

Then the other observation is that, this region has completely transformed from FCC to a BCC or BCT; that means, that entire transformation from one phase to another phase has occurred. And it is like a single crystal of it. This whole region has transformed complete to the lattice has changed; that means, that there is some systematic way in which this transformation is occurring; that means, that it may be some sort of a shear induced or something which happens. So, this is called something like a metric transformation, in many books you will find the name that diffusional transformations are called as civilian transformation.

Then what is another observation. If you look at this region where the surface was initially flat, in this transformation there is some change of surface has occurred that is that is and not only that, the shape of the transforming region appears to be changing. From what it was it has changed to an another shape. These things could be observed using optical microscopy or atom probe atomic force microscopy could be used, to look at the surface relief. In fact, this has been seen. That show that there are lot of distortions are occurring on the sample surface.

So, on the basis of this information, the martensitic transformation is defined as distortive and diffusion less transformation. There is an another word also used as displace transformation. That is atom is displaced from it is position to another position and the displacement or if you look at it less than a lattice translation vector in most of the cases. As I mentioned when we quench the sample up to a certain temperature, there is no transformation. And when you quench below a temperature this transformation starts. This temperature is called as it is generally written as Ms, that is martensite start temperature and then this transformation gets completed at some lower temperature called martensite finish temperature.

In between this temperature, if you cool it from one temperature to another temperature, that is above the martensite start temperature we start take it to a temperature which is in between some temperature you take it to be T 3 in between these 2 temperatures, and if you hold at that temperature and look at that sample the volume fraction of the martensite which has formed remains constant. That is keeping at that temperature for a long period of time there is no change in the volume fraction; that means, that this has nothing to do with, this is also another indication that this has nothing to do with the diffusion which is occurring nothing to do with the diffusion. There are some athermal martensite which are there those part of it because it is not a course on martensitic transformation. So, the subtleties various subtleties regarding this transformation we will not going to it, but we will talk only about the general characteristics.

Essentially it is called as an athermal transformation; that means, which does not depend upon the temperature.

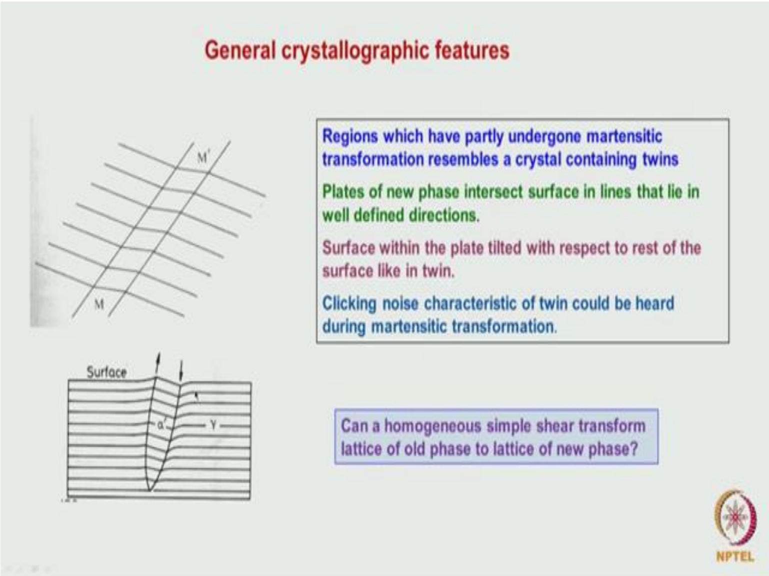
Student: Sir, what is (Refer Time: 06:45) started. It will be the m f m f (Refer Time: 06:50).

With m f we should completed itself.

Student: (Refer Time: 06:55) old in between Ms and m f.

M s and m f someone volume fraction is formed. That is proportional to that is here it is 0 percentage of martensite, and here it is supposed to be 100 percentage martensite. In between the volume fraction will vary from 0 to 100 percentage.

(Refer Slide Time: 07:23)



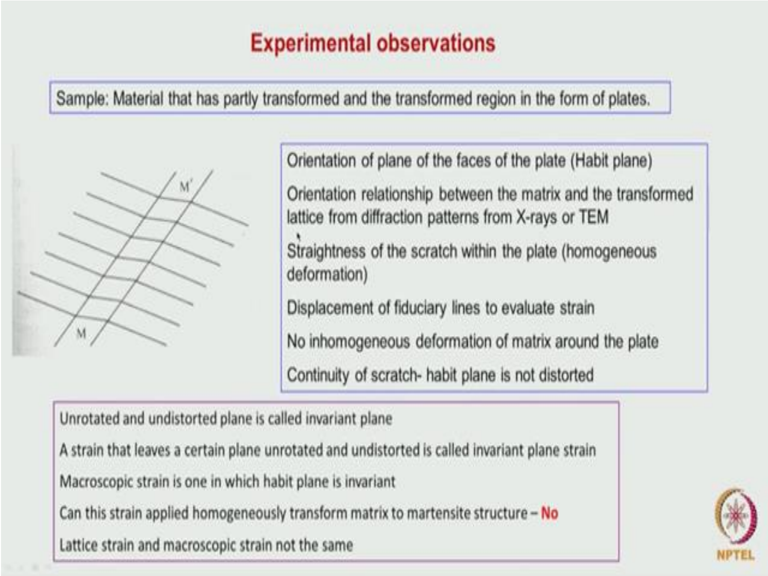
What all the other characteristics by which martensite transformation could be understood. Suppose we take a sample, we wanted to do some heat treatment which is supposed to undergo a martensitic transformation. We polish the surface of the sample then allow you to undergo a martensitic transformation, keep it at a high temperature then quench it quickly. Assume that essentially a plate type of a martensite forms. Then the first thing we what has been observed in this sample is that, when such a transformation is occurring, if this is the sample which is a very polished number assume that a single plate has formed. Then it is seen that this plate essentially forms with some 2 very sharp interfaces that is the first thing which we can be seen. Then another one is if you look at it from the side that is where we are seeing it there is a relief which is being seen on the surface correct.

This is the second observation which we can have. And since the relief is being seen and this line is very sharp; that means, that this looks like typical of twinning. Twinning also the similar type of a behavior is notice. Then it was start that can be applied the twinning theory be to explain martensitic transformation. That was the whole assumption on which this whole martensitic transformation theory was developed.

Then another one what we have to do it is that, suppose in this sample before this transformation has started, this sample it is a plane we can see a surface which is very sharp, suppose in this sample before the transformation, we assume that we have drawn a line like this that is a scratch has been made on the sample surface. Then the sample is allowed to undergo transformation. When what happens is that after the transformation one could see that, this line remains straight up to here, from here to here it is again the remaining straight, though it is changed direction then it goes straight again; that means, that twinning also exactly the same thing happens; that means, that the deformation appears to be continuously their homogeneous deformation which is occurring parallel to this interface possibly correct. That is one of the surmise which we can make looking at this microstructure correct.

And similarly whenever twinning occurs if you do a test we can see your noise which is called click click click click, it will come the sound will come. When you do a mechanical testing you can see that. Similar to this when a martensitic transformation also if you do especially stress induced are strain, but you can hear the same thing. So, all these observations are very similar to that of when a twinning occurs. That is why it was start that whether we can apply the same theory; that means that the question which arises is that, twinning we explained on the basis of a homogeneous shear. Can this be done using a homogeneous shear to transform from one lattice to another with the extent of surface relief or the macroscopic strain which we are seeing it? Is it possible or not the answer is no, but this we will see it the course of the lecture, why it is so?

(Refer Slide Time: 11:32)

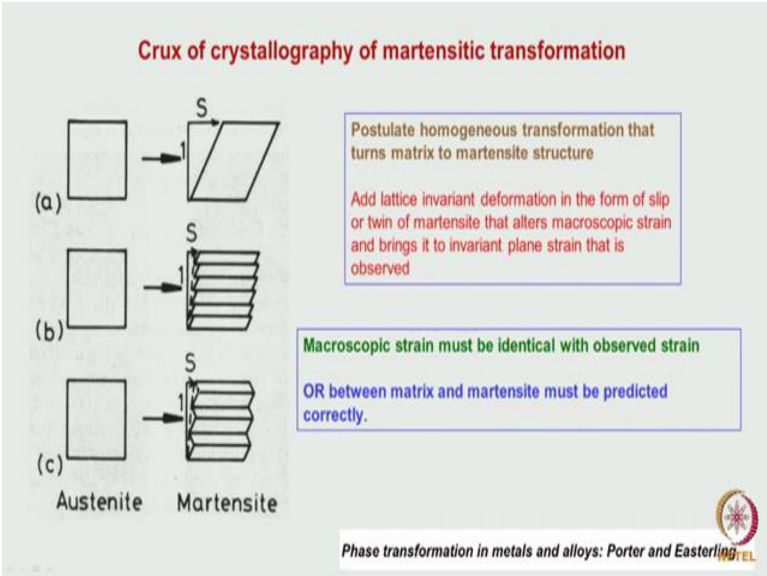


So, as I mentioned we are considering a sample which has transformed. The lines have been drawn, and we see that the lines have been tilted. If you look at these samples, in an optical microscope when these lines are very straight, if it is a single crystal we can find out what is the orientation plane of the faces which are connecting these 2, on this side as this with this is called as the habit plane. That is the plane in which the martensite and the parent face are joint together. If we do electron microscopy from this sample, then I can find out the orientation relationship between the martensite and the parent, and find out which directions match with which directions, all this information we can get it. Then as I mentioned since this line is a quite straight; that means, that deformation could be there homogeneous deformation. And that third is if you look here, this line is straight up to the interface; that means that whatever the deformation with this region has undergone, there is no semblance of any effect strain on that other side.

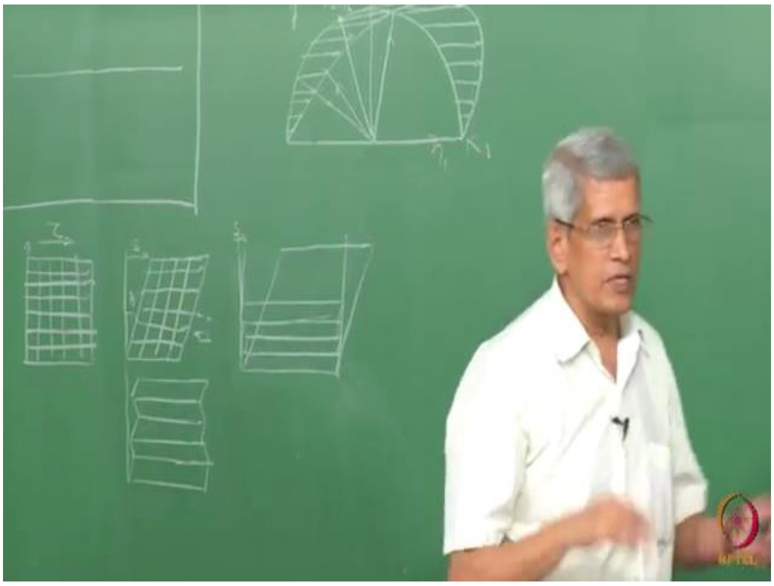
As if this region remains straight up to the just the other region transforms and here again we do not see it correct. The effect of the transformation does not affect adjacent neighboring areas in the matrix. Then this continuity if you look at it this is just joined here; that means, that there may be a continuity between these planes, which are join together. This and; that means, this plane could be undistorted and unrotated plane.

So, any strain which leaves the certain plane unrotated and undistorted, we called such strain as invariant plane strain. That is the definition. As I mentioned can the strain be applied homogeneously to transform the matrix to the martensitic structure? It is no. That is because a strain which is required to transform homogeneously from matrix to that is matrix lattice to the martensite lattice, but there is an another strain which we are seeing it macroscopic strain, both of them are not the same. That we can understand from this figure.

(Refer Slide Time: 14:34)



(Refer Slide Time: 14:34)



Essentially here what we have done it is you take a 2 dimensional square lattice, allow you to undergo a transformation that is homogeneous shear, if you apply it undergoes a transformation to the structure. What is happening? Suppose we have a this is the, that is essentially a square cell, have gone into a parallelogram, their phase transformation as occur. And what is the stream which will be corresponding to this this is going to be the displacement this you can take it to be the shear if you know this angle from which tan theta will be the shear which it will be given. This is the shear which is required to transform from one lattice to the another lattice correct.

Once this transformation is taken, there is a lot of shape changes occur. If we introduce in this lattice, either some slip in this lattice which it occurs, slip by movement of dislocations occurs in this direction. That can change now the lattice structure from here to this is the shape which was originally it was there, now we assume that this is what it is, like this it undergoes a change. Now if you look at it this turns out to be the external surface. This is called as a lattice invariant shear what we are doing it is; that means, that lattice invariant shear means that, this shear does not change the crystal structure, but essentially a shape change it is occurring.

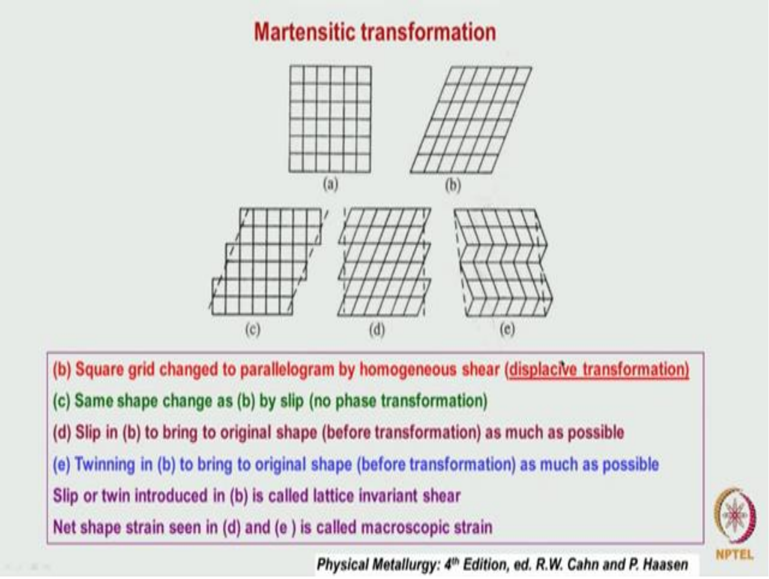
Now, if you look at with respect to this direction, essentially this strain which we see the shape change is very small. This is the observable strain which we are seeing during the martensitic transformation. So, if you see this particular structure, whether it corresponds to just a simple homogeneous shears no, the homogeneous shear has transformed it. Then what we are seeing it is that we have introduced the lattice invariant shear. This could be your slip which we have considered. Otherwise it could be a twin as well. So, twinning means that, so, this sort of a that is it transforms by twinning, when we transform by twinning it has the same crystal structure, but in a different orientation. So, these are all the 2 ways in which this transformation could occur. Both the types of transformations have been observed. Generally, this type of ones which we can call it as lath martensite morphology these are called as plate martensite and twin martensite.

So, essentially crux essentially, of this martensitic transformation cryptography of martensitic transformation, how we can consider is that, there is a homogeneous lattice invariant shear homogeneous deformation by which we transform from the parent to the product lattice. Afterwards we introduce a local deformation which we call it as a lattice invariant shear, with which we can change the try to bring back to the original shape as possible. Whatever is the portion which remains which has not been accommodated, extreme that is what we see as the macroscopic strain. This strain also if you look at it looks like a homogeneous one.

That is what is being observed in the sample. Here what we have done. We have just postulated this is one way in which this transformation could occur. The experimental observations, but we know the crystal structure of the init sample initially, what is the crystal structure afterwards. We can find out from experimental observation what is the habit plane in which it is lying, what is the orientation relationship, what is the crystal structure of the parent and the product, what is the orientation relationship these are all the observations.

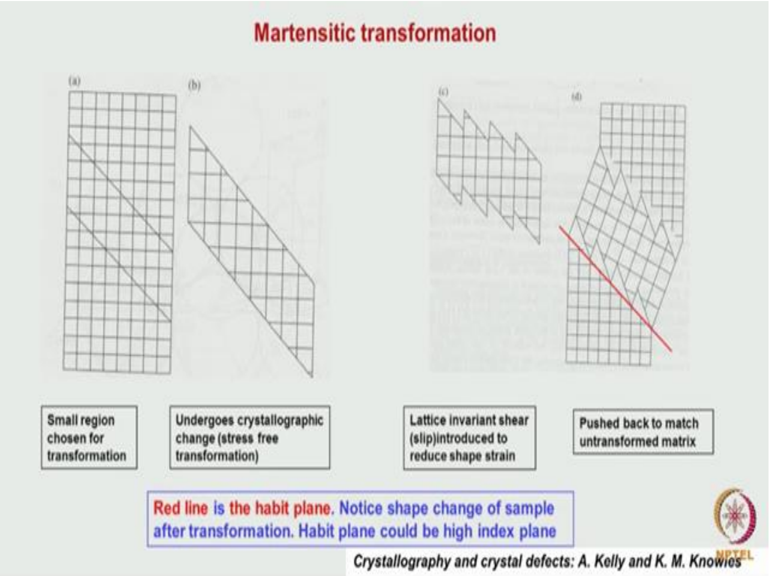
With this theory it is essentially a homogeneous shear or homogeneous deformation. We should try to find out what will be the shape change which should occur whether the macroscopic strain, the orientation relationship, all these things could be predicted by the theory or not. If this theory is able to predict it we can say that this is x able to explain the experimental observation, but this is called as a phenomenological theory, because what is the path which it is taking during this transformation, we do not know. We have only that initial state and the final state we know that we are trying to put forward theory this is the way this transformation might have occurred to reach this final state.

(Refer Slide Time: 20:48)



So, this is essentially what I had shown in this transmission. So, here what has been done is that that inside, the square a 2 dimensional small lattice is also being shown. The square lattice with transforms to a parallelogram and the same thing could have been achieved. This shape change could have been achieved through the slip taking place homogeneously in the material, but though the shape change has taken place the crystal structure has not undergone any transformation correct; that means, that this is not a martensitic transformation, but once this shape change has taken place as I mentioned, either by slip within the transform lattice or by twinning within the transform lattice, we can try to bring it back as close as possible to the original shape. Whatever the remaining strain is what it comes as the macroscopic strain which we are seeing it. We have we will look at it, how this macroscopic strain is accommodated that is also very important. This I have already explained.

(Refer Slide Time: 22:02)

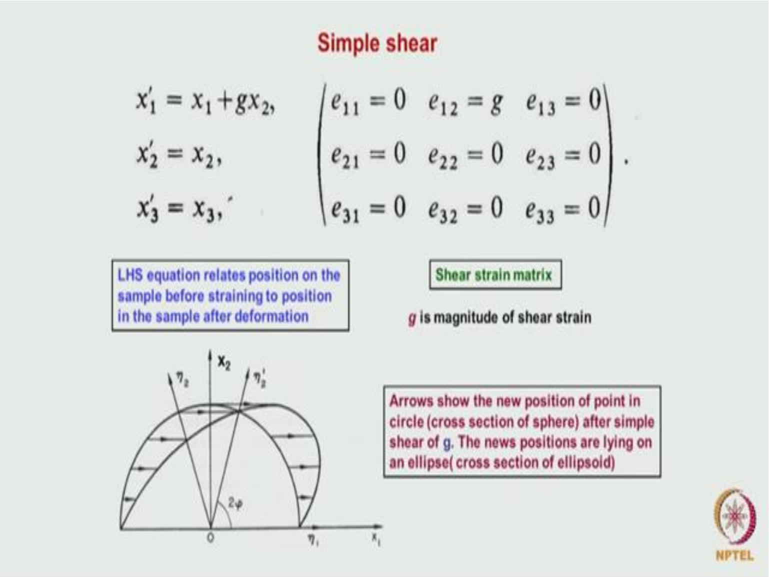


Here I had shown the same thing which have done. It is a lattice which is a square lattice we assume that this region undergoes some martensitic transformation. As you might cut it out allow you to undergo a martensitic transformation. It has undergone a shape change. Then introduced slip into it to bring it back to the original shape. To as close as possible to original shape, if I try to introduce this into this lattice, what I should do normally, I should just apply some surface tractions. So, that the shape is brought back exactly to this shape and introduce into it. Once it is introduced into it then you allow it to relax. When we allow it to relax the part of the matrix and this transform phase both will take care of this strain correct.

That is how it will be accommodated, but in the experiment which we mentioned the lines if we look at it, write up to this point, there is no change in line; that means, that there is no strain is getting accommodated.

So, what is the only way it can happen then is that, you just rotate this as such like this. So that it matches with this shape and try to fit it at this interface, where it has been cut which is the habit plane. Then it is in a rotated shape the other portion also connected like this because when it has been initially cut it has been connected parallel to these 2 line. So, this now if you look at it, there is a surface relief has come. So, essentially this rotation is what you are seeing it is surface relief. That is also a part of a strain only correct. So, that is what we are observing it as a macroscopic strain or the macroscopic surface relief which we are seeing it is this change is it clear. So, this red line which I have done is the habit plane which is joining these 2 faces. This habit plane could be high index plane this we will shortly look into it how to find out this habit planes.

(Refer Slide Time: 24:19)



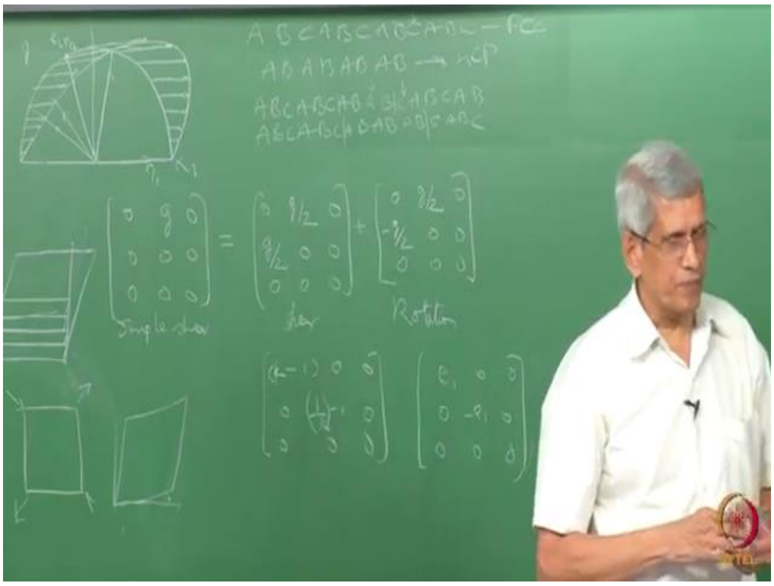
The crystallographic theory we will look it. Before we go further let us recap that because we are talking about this transformation and as I mentioned, So, many times homogeneous shear which is taking place in this material, let us look at the characteristics of a homogeneous shear before we go into the martensitic transformation theory.

Suppose a simple shear is one in which in only one direction a shear strain is being applied. What we have taken is essentially take a hemispherical sample of the material, here we apply a sequence shear g is being applied. Then what it will happen is that, this will transform into a elliptical shape. Because one is one direction the shear is being applied. So, when the shear is being applied the matrix can be written in this particular form. So, g is the simple shear strain correct. So, essentially what is going to happen is that, if this is the origin of the origin core of the coordinate system.

It has been each of these points on the surface by the simple shears gets transformed to a corresponding point that is correct. This is how the transformation is occurring; that means that suppose I look here, this is the original vector from here to here. Now that has transformed into an another vector, which essentially has it is length has been shortened; that means, that most of the lines are undergoing a distortion, but there is one particular line which essentially the magnitude from here, it has come to this one, which has not undergone any transform this is an these are rotated, but not the distorted.

Since we are considering only a simple shear in this direction, perpendicular to it if were locally look at there is no change. So, there is a plane which is passing through these directions, that plane is a unrotated, that is rotated, but distorted undistorted plane, rotated, but rotated and also undistorted. Whereas, since we have held it here the strain will be 0, correct shear strain. This is the plane, which is unrotated and undistorted this plane in twinning morphology we call it as K 1 plane the plane which contains here this called as K 2 plane that this direction is called as theta 2 the direction here is called as theta 1. This you are familiar with it in recently only we have had lectures on this aspect correct.

(Refer Slide Time: 28:04)



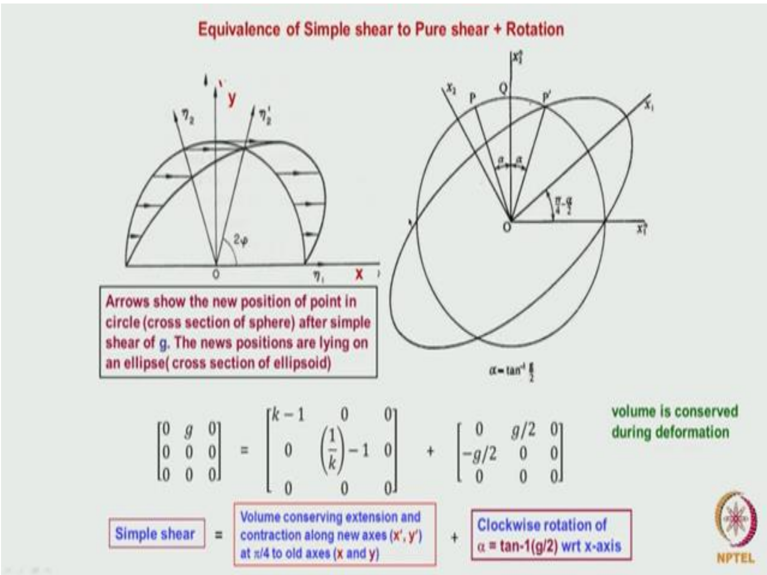
So, this is one characteristic that is a plane gets rotated undistorted. This is because the same transformation we could consider it in a different way that is this is this is how the strain tensor we are writing it correct. This itself could be returned as equal to, this is pure shear. This is a rotation shear rotation. And this is we call it as a simple shear. This is what as. So, simple shear consists of a pure shear plus rotation. And we know that if pure shear is being applied, this is equivalent to that is or applied we can find out some principle strains in which the shear component becomes 0. That is only principle strains are there, which is pure strain correct; that means, that the pure strain is essentially going will be that in tension in one direction and compression in another direction. This axis generally when the strain is mark is at 45 degrees with respect to the axis in which the shear strain is being applied.

Then we will be able to write this into an another strain which is written as, what is K here essentially is nothing, but the total extension which we see in a unit length of a sample. So, K minus 1 gives the strain part of it, is this clear. So, essentially what we can consider it is that, by giving a strain this can be written as something which is similar to in this which can be written in this form, that is something like because, So, that the total when shape change does not take place. The some of the diagonal elements has to be 0 correct.

So, in this form we can write it. So, essentially what is required is that, the simple shear is equivalent to considering yet tension in one direction and compression in another direction, along principle the strain directions. And then if you give an appropriate rotation also corresponding to this one, we can bring back to this original shape correct. These clear. So, the simple shear is equivalent to both the ways we can consider. It is the simple shear can be considered as giving pure shear in 2 directions, and that is this if you remember I had shown that if you consider a square, if you apply if you apply a pure shear, this will change it is shape to this particular shape correct. And then if you give a rotation it will be coming back to the shape like this like a simple shear.

Now, this same shape could be achieved by taking the square and pulling it in this direction and compressing it in this direction also it could be done. Why we considered this? The reason is very simple that in most of the martensitic transformation when a crystal structure goes from one structure to another structure, by pulling in some direction and compressing in some directions in to the unit cell. We can make the requisite shape change. That shape change can be considered as equivalent to that is if we can transform it to some way where it looks resembles like this sort of a strain matrix. Then the same theory could be applied the homogeneous deformation theory could be applied. Only a rotation has to be given to bring it back to the original shape.

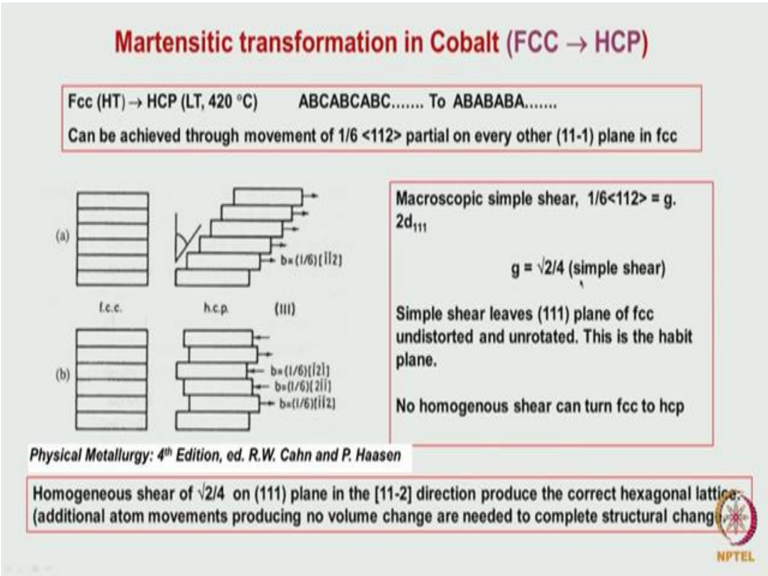
(Refer Slide Time: 33:29).



So, this is exactly what is being done is that, the same thing could be that is what I had shown here. This is the sphere of the original sample. And we have pulled in these directions it has undergone a transformation and this is how it looks like. And this can be written as equivalent to this is the way it is plus the rotation will be required. Now we will find out how we go about and give these distortions to the sample to get the requisite changes to the parent lattice. So, that we are able to generate the one side structure.

Let us know you what you have to remember here is that the simple shear is equivalent to essentially we have tension and compression in directions which distorts the shape and the rotation which is required to bring it back to the transform stage. That is essentially what is which will be implying in this analysis.

(Refer Slide Time: 34:44)



Let us consider some specific case. One martensitic transformation in cobalt let us consider. This cobalt is at high temperature it is hexagonal close packed. It transforms to face centered the closed packed, that the face centered cubic lattice at lower temperatures below 420 degrees centigrade. So, above 420 degrees centigrade it transforms to HCP. What is the stacking sequence in these lattices? It is essentially A B C A B C is the stacking sequence in HCP.

Student: A B.

A B A B A B is the stacking sequence will hexagonal close packed. Suppose I introduce a stacking fault in this lattice at any plane suppose we assume that in this direction we are introducing a stacking fault we are introducing a stacking fault here. Then it will become A B C A B C A B C goes into A A goes into B. Then this is C A B C. This is how the stacking sequence becomes. So, we have an A B A B type of a stacking sequence which has come. Now if I introduce a stacking fault again, here that is here we have introduced here, that is the transformation is from here, now we are leaving one and an alternate layer we are doing it then what it will happen A B C A B C A B A B this C will become a this will become B A B C right. So, now, you see that; the thickness of the.

Student: h c p.

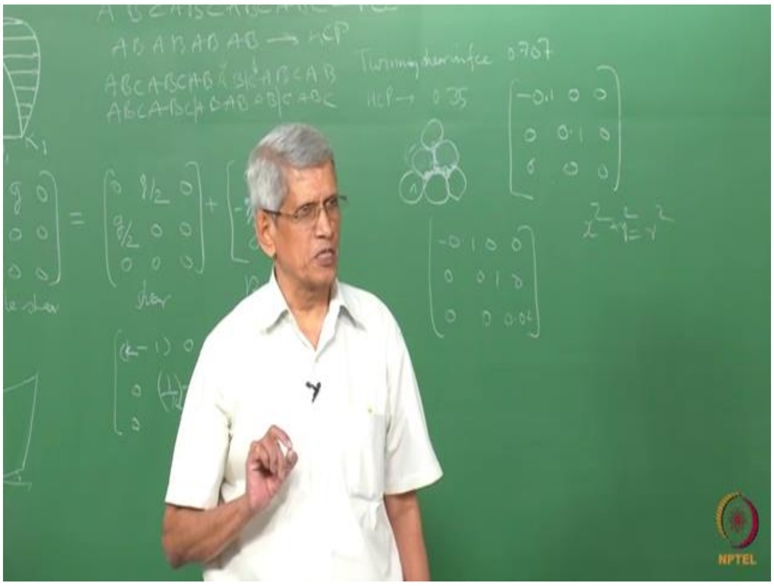
H C P is increasing, but what one should remember here is that this is done through introducing stacking fault in every alternate layers. Not on every consecutive layer. If you introduce tracking fault in every consecutive layer we form a twin of the FCC lattice, but on every alternate layer if you do it we can increase the thickness of the HCP lattice that is what essentially is being show.

Student: (Refer Time: 37:28).

No, that depends upon the temperature chemical free energy change which is going to take place that is even if, when we generate one lattina defect that is one partial passes through a plane it is generating here let us stacking sequence which is A B A B has come; that means, that a nuclear of HCP has already formed, but if it has to grow it all depends upon what sort of a free energy change which is available when it goes from one phase to another phase transformation. The thermodynamic equilibrium phase change if it has to occur the free energy change also should be favorable. Then the otherwise this will be only just remaining as a fault it will not grow into that phase.

So, here the FCC lattina at every 2 layers, if you introduce a stacking fault. Then essentially we have transformed this into an A B A B to hexagonal lattice correct. What will be the shear which will be associated with this sort of transformation because it is not in one layer it is or 2 layer. So, the shear will turn out to be root 2 by 4.

(Refer Slide Time: 39:08)



It is a simple shear which it is occurring, but the value of this shear will be the case of twinning and every layer when it occurs we found that the twinning shear in FCC is 0.707. This value will turn out to be or HCP this should be every alternate layer means that the shear will turn out to be.

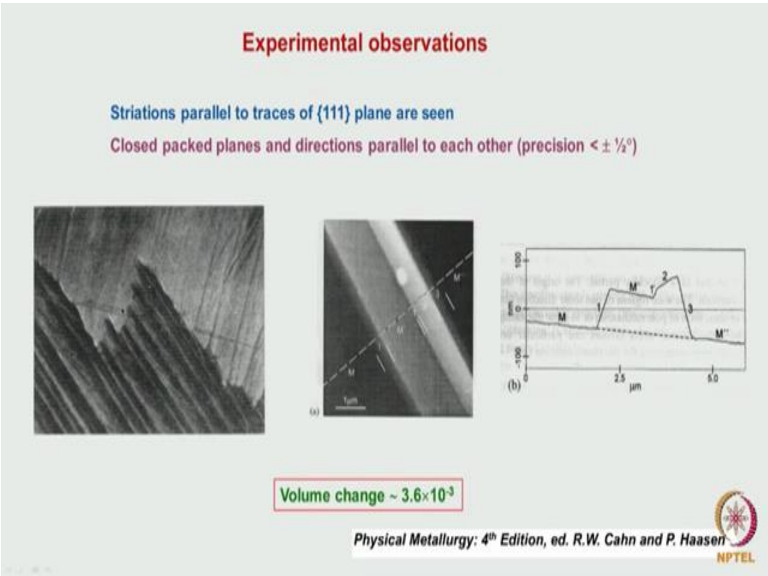
Student: 0.35.

0.35 half of that, shear this will be the twinning shear which is required. And another is the plane over which this layers the FCC and HCP mixed is along 1 1 1 plane of FCC parallel to 0 0 1 plane of HCP. So, that becomes the habit plane, but this involves a lot of shape change which has happened. Instead if on some layers it is in this direction. And we have studied earlier that whenever atomic movement takes place in a hexagonal close packed plane. Let us consider a 2 dimensional hexagonal lattice.

An atom setting if this is A position this is B position this is A C position. So, from this C position any movement which takes place either in this direction or in this direction the partial moment it all takes to B position correct. So, it does not matter which is the shear vector which is being used. So, instead of b equals 1 by 6 1 bar 1 bar 2 and 1 1 1 plane if B equals 1 by 6 to 1 bar 1 bar 1 direction B give a shift. That will also create A B A B type of a stacking sequence; that means, that the HCP lattice is being done, but if you look at the amount of displacement which is occurring in each of this direction they turn out to be very small.

So, that is what essentially we considered nearly the same shape is being maintained here. So, the macroscopic strain which we are seeing it is going to be negligible, in this case. In fact, experimental observation is that this is indeed so, but what we should understand these that suppose we try to give a homogeneous shear. Because we said that this is the shear which is simple shear which is required, but if this shear is given homogeneously to the entire atom every alternate layer atoms will become to a correct position, but in between layer will not be brought because it will be half of that shear which will be given should be shifted to position. So, as I mentioned like in twinning some shuffles will be required to bring them to the correct position that is what possibly might be occurring right.

(Refer Slide Time: 42:32)



So, with that shuffle a complete structural change would take place. These are some experimental observations, is that the same thing in a cobalt with some a lying addition I think nickel has been added to stabilize this FCC phase. So, that part of the FCC phase remains during the transformation. This is the transformed region which is an HCP. If you look at this this lines which are there this direction. These are all a 1 1 1 corresponding to intersection of 1 1 1 planes with the surface.

Then between closed packed planes and closed packed directions. Some electron microscopy are x ray diffraction try to find out what is the orientation relationship it has been seen that the planes and direction, are within plus minus half a degree have been precisely measured. That is what it has been observed then in these sort of samples when an atom probe microscopy is taken.

One can see that there are some steps which are occurring not atom probe atomic force microscopy. Then we look at it atomic force microscopy will give the depth information of the height varies. So, we can see that there is some variation in height which is occurring. This variation in height could correspond to here if I take and probe across it you find that there are some height changes which are going to take place this is exactly what it is showing. So, some region has shifted in one way another region shifted in another way. So, it looks like a corrugated structure correct. And a people have tried to calculate what is the whether there is any volume change which is taking place because atoms are shifted from one position to another position and it takes place over a second layer a small change in volume has been noticed and this change is about 3.6 into 10 to power of minus 3 this is what essentially.

Student: (Refer Time: 44:40) lattice parameter does not changing they shouldn’t change (Refer Time: 44:45).

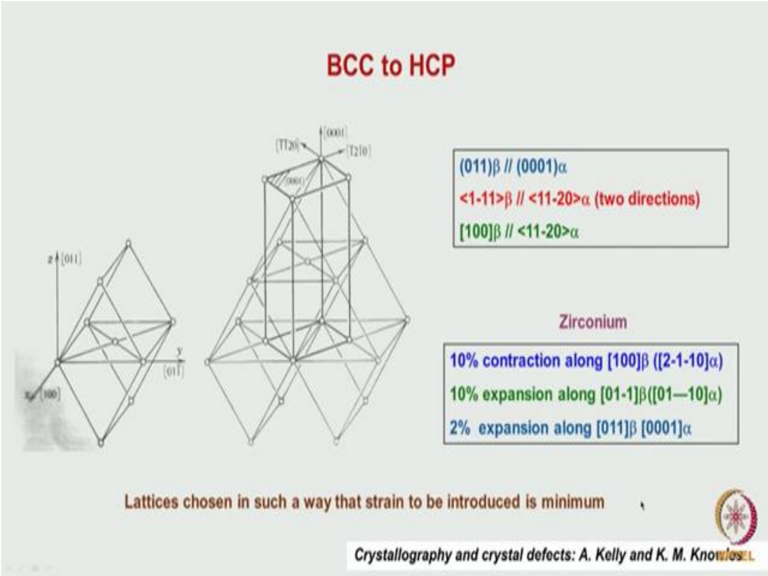
Which one there is a there is a c axis will change a little bit.

Student: (Refer Time: 44:49).

Yes, slight change will take place that is what it gives the small change in volume.

Student: (Refer Time: 44:54).

(Refer Slide Time: 44:59)

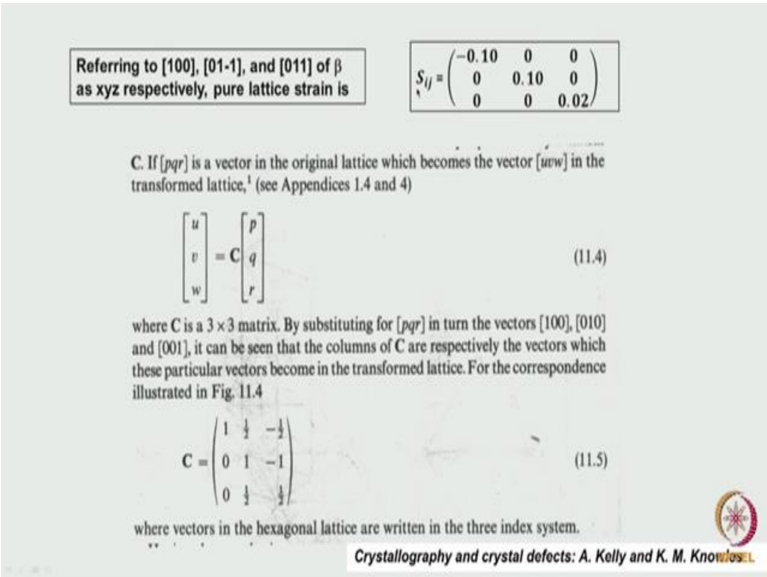


Let us consider on another case which is essentially a transformation from BCC to HCP. Zirconium titanium all this material at high temperature it is BCC. They transform to an HCP, has lower temperatures. And this transformation essentially occurs martensitically. How can we view this change from BCC to HCP? The way we mentioned first let us consider a unit cell of BCC. And then we will apply some shear transformation to change it from BCC to HCP homogeneous lattice shear which we are giving it to transform it.

So, far that the unit cell which is being chosen is such that it contains it is a non-primitive contains 2 atoms per unit cell because HCP also contains 2 atoms per unit cell. It is chosen in such a way that this is 1 0 0 direction this is 0 1 1 bar directions this is 0 0 1 bar direction. This is of this unit cell looks like to this unit cell if I give some distortion, along at it in one direction compress it in another direction and along it maybe in another direction. I can by introducing these shape changes we can transform it to any shape which we want to. So, these changes back changes or this changes to the hexagonal unit cell. To achieve this type of strains which are required is in this direction yet 10 percentage contraction is required. There is along 1 0 0 10 percentage expansion is given along 0 1 1 bar directions and a 2 percentage expansion along 1 1 0 1 1 directions this is all with respect to a BCC lattice.

Since it has transformed to an HCP, now we know that what is the we can find out the orientation relationship also that is 0 1 1 of beta corresponds to the basal plane of alpha it has become this plane because it is perpendicular to this direction. And then the direction 1 1 bar 2 closed packed directions are there that has transformed to 1 1 2 bar 0. And this third direction has transformed to another 1 1 0. So, essentially all the 3 closed packed directions of external lattice has been generated in this structure this way. And we can choose any type of a lattice that is whether this sort of a unit cell has to be chosen. Or can we not choose in BCC any other type of a unit cell. And try to applying shear we can transform it to this particular cell it is possible always, but the thing is that we choose a cell which requires minimum distortion. By giving minimum strain we can transform it. That is what we have chosen. And when we give strain in these direction this strain is uniformly applied. So, it is a to the unit cells throughout the lattice it is being applied. So, it is a homogeneous deformation which is taking place correct.

(Refer Slide Time: 48:52)

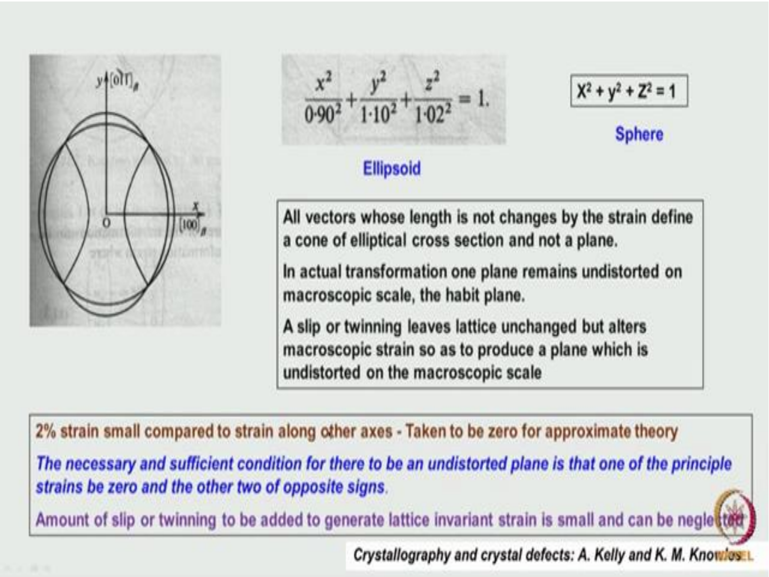


And another is that, we have studied earlier that when we have given such strain and deformed from one lattice to another lattice. We can using the lattice correspondence we can find out the directions and planes corresponding to the same direction in each of the lattices. That is what essentially the matrix corresponding that is given what is the strain matrix here. The strain matrix now it turns out to be in terms of the BCC these 0.1000 this is,

Student: 0 2.

0 2 this is exactly what it is. Now if you look at this strain matrix. This is positive this is negative this is a very small value. How this shape change can be represented this shape change can be represented; that means, this should become an ellipse side of revolution correct. So, essentially an ellipse side of revolution that is, suppose we take a portion of a sample which is a sphere with the orientations which we have chosen and then try to give the respective elongations 10 percentage in 2 directions and the 2 percentage in other direction. So, that it has become an ellipse side correct.

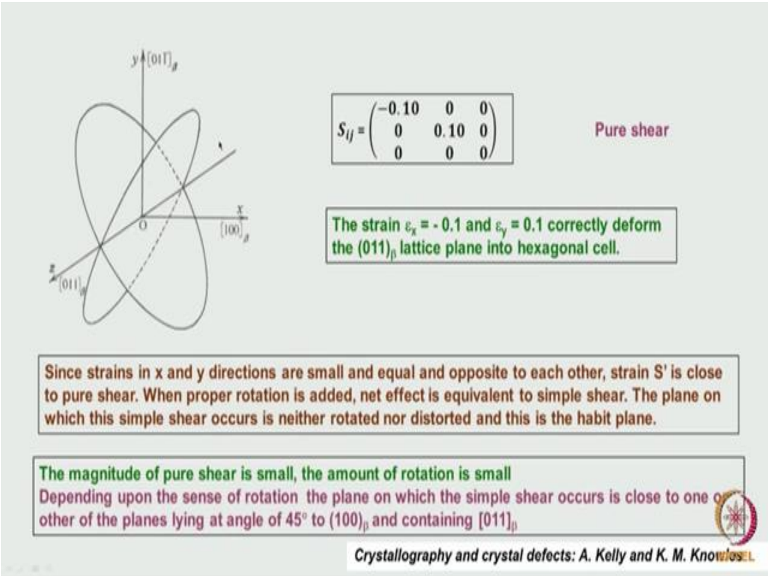
(Refer Slide Time: 50:32)



And if we try to join both of them together that is superimpose not joins superimpose one on top of the other, we will find that there is some vector here on which the sphere and the ellipse meet; that means, that in those directions, the magnitude of the vector remains that same. If you try to look at the locus of that that will turn out to be a circle and the surface 2 circles and this will be joined by to the center if you see it is something like a cone; that means, that for a simple shear what we have considered, a homogeneous shear simple shear which we have considered, there is a plane correct for that plane to be generated if here applying strains along principle direction, one direction contraction one direction expansion if he give it, keeping the volume constant. Then that plus or rotation can be equivalent to a simple shear. So, that a plane which is unrotated and undistorted will come, but that will not happen here. If this has to happen what we have to do is that the strain matrix the one strain which is there do something apply some deformation to it locally. So, that the strain is compensated that becomes zero.

In this particular case what is essentially is being done, is that since the magnitude is very small an approximation is being done. That it is so small that we negligible. We can go ahead with that that is why in otherwise, how that accommodation is d1 by either slip which is taking place in the sample or a lattice invariant shear which is a twinning also can compensate for that, so that that component can be made 0. Then the strain matrix will now can be changed to right. Once it has been changed to this form it is very easy to handle. That is essentially what is being given mentioned here 2 percentage strain is small compared to other axis taken to be approximately 0. Then the necessary sufficient condition for there to be an undistorted plane is that one of the principle strains are 0 and other 2 are of opposite sign; that we are able to achieve. How that one strain is being made 0, it is by lattice invariant shear which we can add by either slip or twinning.

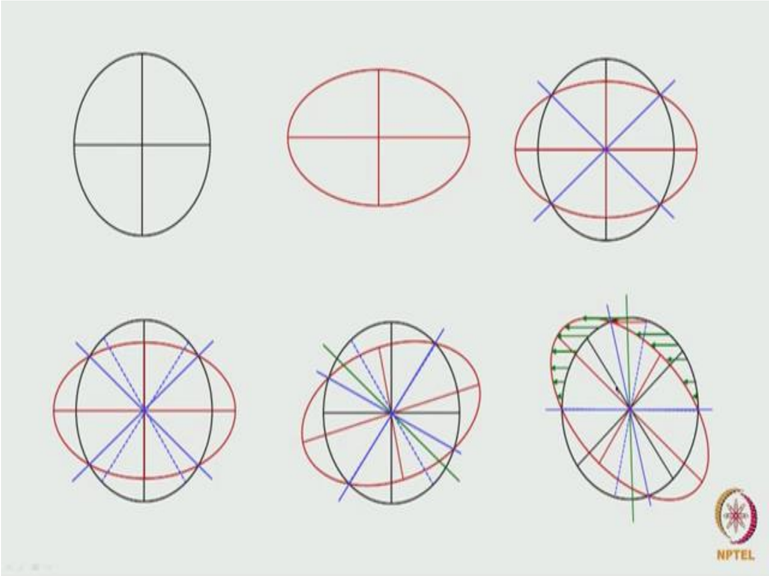
(Refer Slide Time: 53:48)



Once that has been done, now if you look at it we have instead of a cone. There are 2 planes or circles which are intersecting each other correct this is essentially what is happening.

Now, you see that there are 2 planes which are there, these plane will be inclined at some angle with respect to these coordinates and this is we are marking all with respect to a coordinate system of the unit cell of the be BCC which we have chosen right. And this brings out 2 planes by rotating one of the plane, we can bring it to a position which is unrotated and undistorted how we do it.

(Refer Slide Time: 54:36)

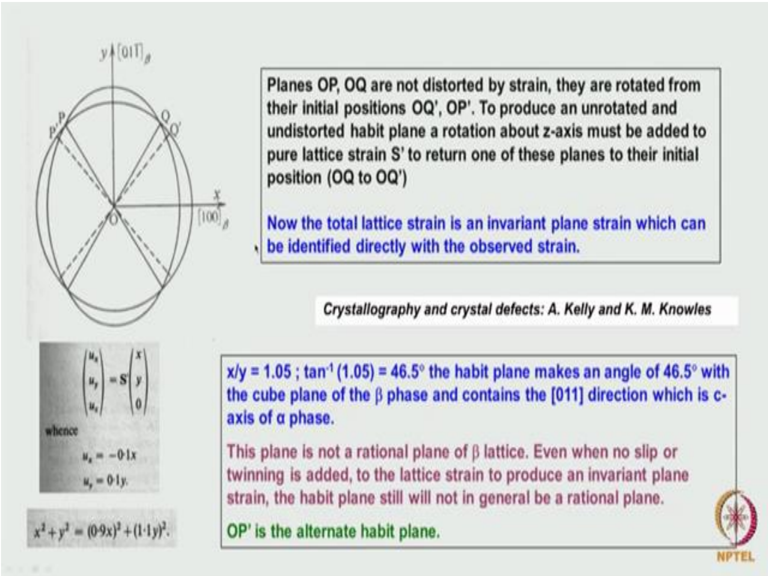


We will just look at it now. We take this case this, this is a part of cross section of a sphere which is a circle this is a coordinate system. This one I had given some elongation that is compression and tension. So, the volume is kept constant it has reached this shape. When I superimpose these are all the vectors where they remain that same, but where from this vector has come, when I have compressed it in this direction and expanded it in this direction some point which is here on this that has rotated and moved and shifted and come here, that is why it is appears the same like in the deformed lattice, that is in the ellipse the point, which is there under sphere when it has undergone some compression and tension has moved from this point to this point. That is why they appear as the same that is what essentially is being shown in this figure.

Now, this is very clear. In these this is the original point from which we have started now it has rotated and reached here. Suppose I give a rotation in this direction to this one, that is the whole this deformed one if I rotate it. This point will come back to this original position. And time when that joins what I am showing it with the green line is the original position of this one now when this is being rotated this also gets rotated and comes here. And that has reached here; that means, that this plane has become a unrotated and undistorted plane gather joined together correct. And the plane which was there originally here has been rotated and has come here because the magnitude of the vectors on this plane remains that same.

So, this is equivalent to a simple shear that is exactly what now I have, just showing it keeping this plane rotating this and just showing it. So, essentially with a set of these figures, you can understand that how we can bring make a habit plane which is rotate unrotated as well as undistorted; that means, that after giving this transformation, some rotational force to be added, that rotation is also dictated by the shear strain correct.

(Refer Slide Time: 57:25)

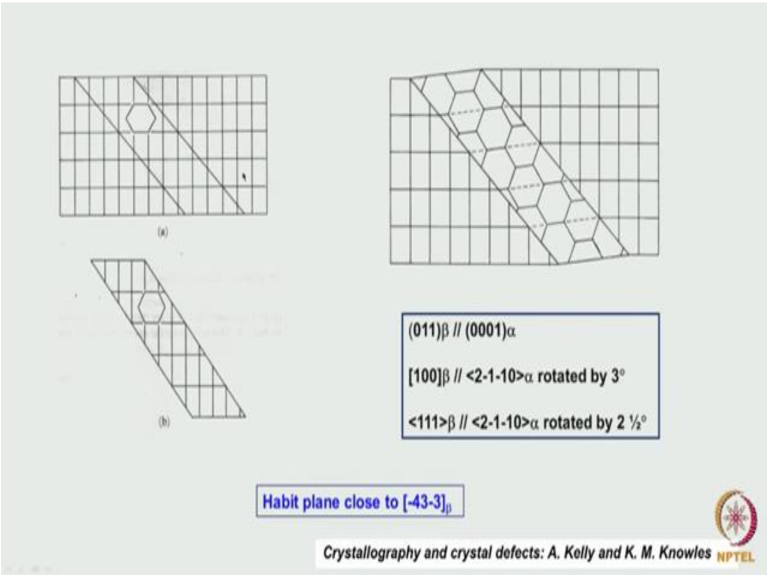


So, here now if we look at it in this particular one exactly the same thing which I had shown here that is one is this vector which has essentially rotated and come here. So, this is the sort of a rotation which has to be given to join. Since we know, this is the common point what is the coordinate of this one, because this point is on the circle correct q dash which is rotate it is coordinates are nothing.

But essentially we can write x squared plus y squared equals r squared, if you know x and y value. Similarly, this point which is going to be here has come from displacement from here to this one suppose this is x and y, using the strain matrix we can find out u x and u y and u is said we can find out. That value turns out to be this 1 minus 0 0.1 x and minus that is u y equals 0 0.1 y. And since the magnitude remains that same here also x square plus y square should be equal to the same as this magnitude. So, we equate this and we can find out the ratio of x by y. The ratio of x by y will be tan inverse this angle which it makes from here to here. Now we know what is the angle at which this plane is lying. And since we know this direction and since we know this direction, we can immediately find out what is the direction in which this vector is lying and the plane which is contained in it.

Since the displacements are very small here, this angle turns out to be around 46.5 degrees and this plane when it has been founded that value turns out to be some 4 bar 3 3. This is a high index plane. Is it clear? This is how we can essentially because the habit plane is the one which is unrotated and undistorted. This rotation has to be given to this one to bring into the original one. That rotation is what it appears as the strain the macroscopic strain which we observe is that particular one.

(Refer Slide Time: 59:58)



That is what essentially is being shown here in the crystallographic way, that is a cross section of the lattice is being shown this is a 0 1 1 plane of BCC. And this is what is allowed to transform to hexagonal lattice, by whatever is the transformation matrix which we have discussed now the crystallography we are allow it to transform. After this has transformed there is a slight orientation might have taken place, and when we try to fix it here. You have to match the planes match it to match it this has to be rotated a little bit on match, and this if you look at it if you draw a line this is what the rotational strain is rotational. Also we considered as part of a strain that is if a matrix cannot accommodate the strain by deformation, it will try to rotate correct.

So, that is what essentially is happening in this case. And now we can see what all the directions these are all the directions. This is a 0 1 1 of beta is parallel to 0 0 1 of 0 0 0 1 of alpha basal plane 1 0 0 of beta. Since some small rotation has been given to accommodate this at the interface, so that the plane remains an unrotated and undistorted plane because that has to be join together correct. Then this direction to 1 bar 1 bar 0 of alpha is rotated from this direction by about 3 degrees. 1 1 1 direction of beta the other direction which is parallel to closed packed direction nearly parallel to closed packed and it is rotated by 2 and a half degrees.

Then when orientation relationship has been found in these samples using the T m on the examination of the samples then orientation relationship has been found out. It has been noticed that about 2 to 3 degree is the mismatch which can be found out between these orientations that matches well, and the habit plane was found close to 4 bar 3 3 bar and experimentally determine habit plane from analysis of micrographs also turn out to be the same value. That is why now we can say that this sort of looking at analysis of martensitic transformation matches very well with a prediction. So, that way to us decide at the yes this theory will work. Now the next question comes is that there are many cases where the strain in the third direction is not negligible.

For example, in the case of iron martensite, this case we will consider it in the next class. Next class we will take one or 2 cases. And how this is compensated we will talk about it. We will stop here now.