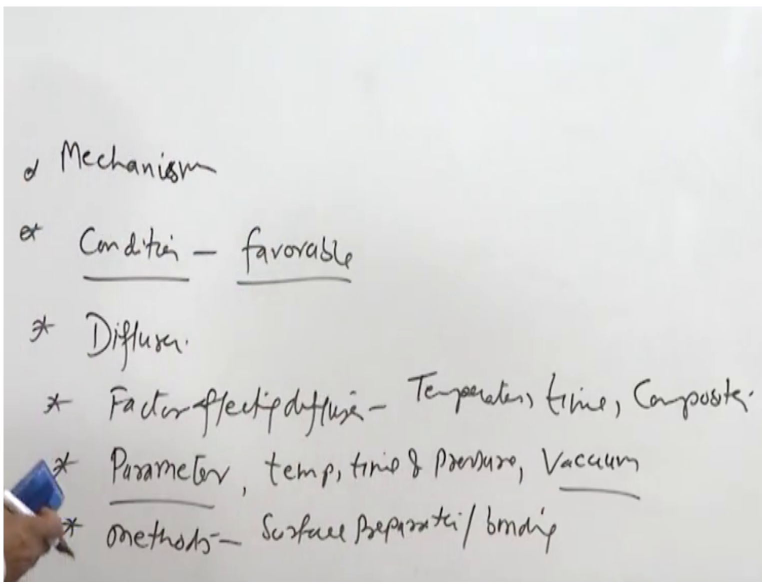
Joining Technologies of Commercial Importance

Dr. D. K. Dwivedi
Department of Mechanical and Industrial Engineering
Indian Institute of Technology - Roorkee

Lecture - 25
Diffusion Welding

Hello, I welcome you all in this presentation, this presentation is based on the Diffusion Bonding process, this is one of the solid state joining processes and it is related with the joining technologies for the metals. So in this presentation we will see that how the diffusion is actually used for development of the joints.

(Refer Slide Time: 00:46)

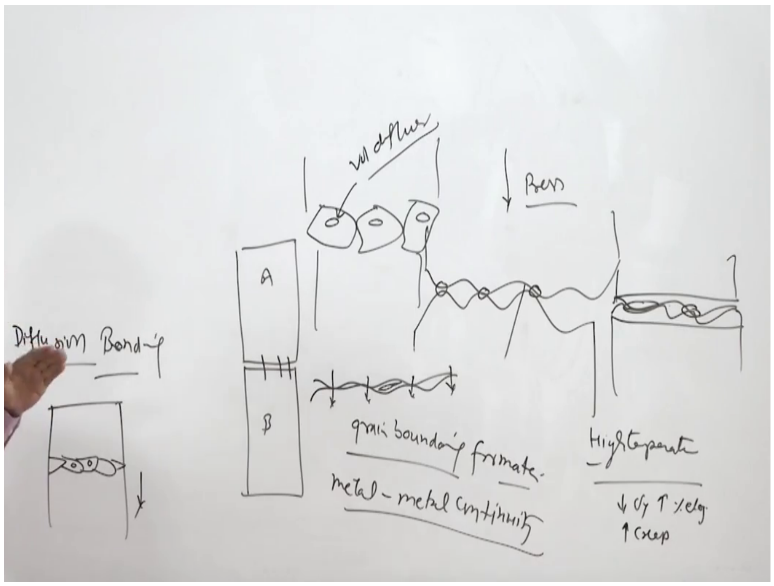


And this process is, so different aspects related to this process starting with other mechanism of developing the diffusion bond and then the conditions where this kind of process is favorable, so favorable conditions where this process can be effectively used, then we will talk about the more about the diffusion related aspects and then the factors affecting diffusion - factors affecting diffusion like mostly temperature, time.

And maybe sometimes the compositional aspects the composition of the metal systems which are being joint and then we will see the parameters related with the diffusion bonding, parameters like these are temperature, time and pressure apart from this another one is the level of vacuum which is used for the diffusion bonding also plays a very specific role and the method of the diffusion bond - methods of the diffusion bond involving like surface preparation.

And then the bonding so we will try to talk about all these aspects apart from the limitations related with these processes and what are the efforts being made in order to overcome those limitations so that the processes can be made popular.

(Refer Slide Time: 02:41)



So as far as the diffusion bonding is concerned like say this is mostly used for the - this is mostly used for the metallurgically incompatible systems - metallurgically incompatible systems, so say like one side we have system A and another side we have system B and the 2 are to be joined, so the joining will be facilitated - joining will be facilitated through the diffusion across the interface so mating surfaces first are brought in contact - mating surfaces are brought in contact.

So whenever this contact they are brought in contact initially contact at the mating surfaces is very localized, so like say contact is here little bit here or little bit here so very actual contact area is very small, so in order to so means metallic continuity is very small right now so in this case when the pressure is applied initially application of pressure will collapse or deform all the asperities peaks and valleys so that by the plastic deformation things come closer.

And we will see that the- the two sides have really come closer and the gap is left here and there, so when this is achieved at high temperature - at high temperature means at high temperature the systems have been kept at high temperature under pressure so the deformation is facilitated in number of ways, one reduction in yield strength, increase in percentage elongation.

And the third is increased creep of the material especially near the contact areas contact near the mating surfaces locations, so the creep plastic deformation under the stresses facilitate collapses the peaks and valleys and so the metal to metal contact increases once the metal to metal contact increases the diffusion like this like say most of the things are in metallic contact so diffusion across this starts and the when the diffusion is starts the grain boundary formation takes place.

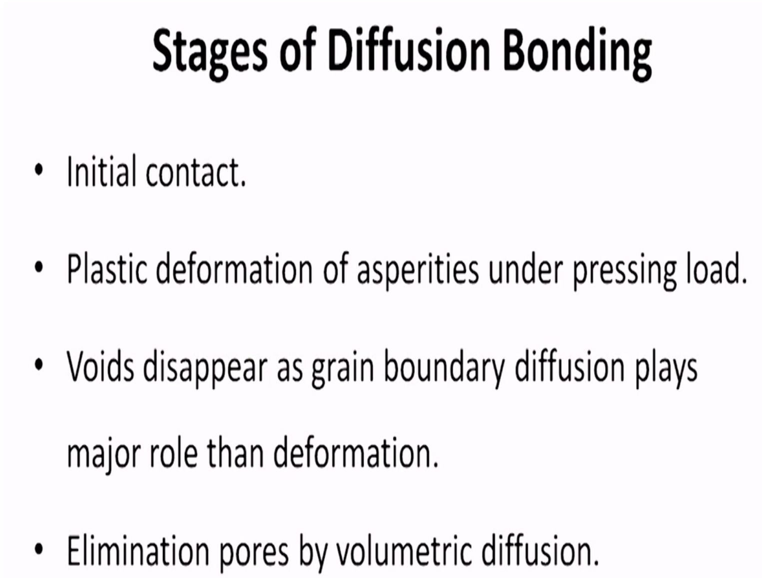
So grain boundary formation across the interface occurs grain boundary formation this is the stage which is required for metal to metal continuity or the metallurgical continuity resulting in the metallurgical bond, so the when the grain boundary formation starts will see that these the areas where the metal to metal contact does not exist, these areas will start getting reduced significantly and gradually.

We will see that material grains have been formed all along the interface and the pores are left in between like this so the grain boundaries across the interface have been formed but the pores are the unbounded areas are left with in the grain, so in the third stage or fourth stage the volume diffusion facilities - volume diffusion facilitates the removal or elimination of these the voids or the porosities left with in the grain.

However the porosities like this is the system which is being joined and the grains have been formed at the interface like this and if the pores are left within the grains then these are not considered to be very harmful for the mechanical performance or mechanical properties of the weld joints because these are within the grains and they are very localized and their shape is spherical so they are not that damaging.

But still if the diffusion is continued for long then all these voids are eliminated by volume diffusion step or the mechanism of the diffusion bonding so basically it involves the first the initial plastic deformation followed by the creep and then grain boundary formation by the diffusion across the interface and then volume diffusion for elimination of all these voids takes place for development of the diffusion bonds.

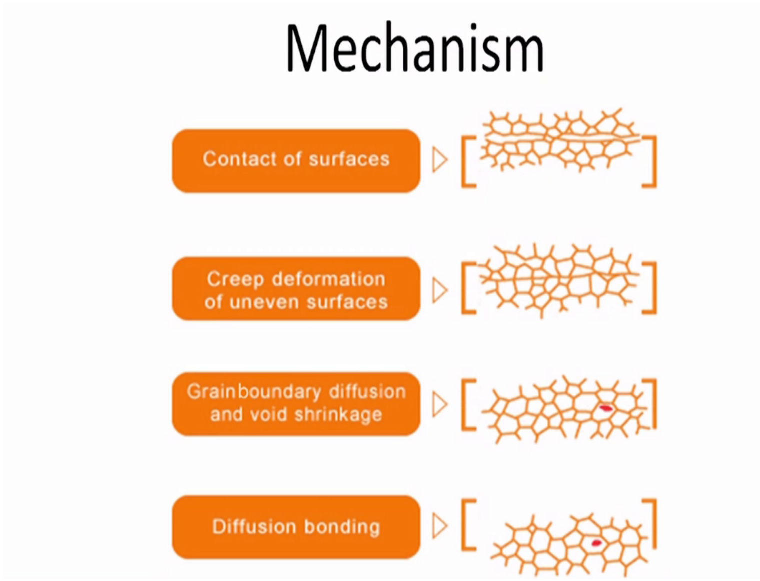
(Refer Slide Time: 07:47)



So this is these are the steps is initial contact then plastic deformation of the asperities under the load and then void start disappearing gradually as the diffusion proceeds and the grain boundaries are formed and thereafter once the grains - grain boundary deformation starts the pores will start getting reduced and at the end when the - the pores are localized within the grains.

The volume definition of the - volumetric diffusion helps in elimination of these voids and pores from the materials, this is what has been shown in schematically.

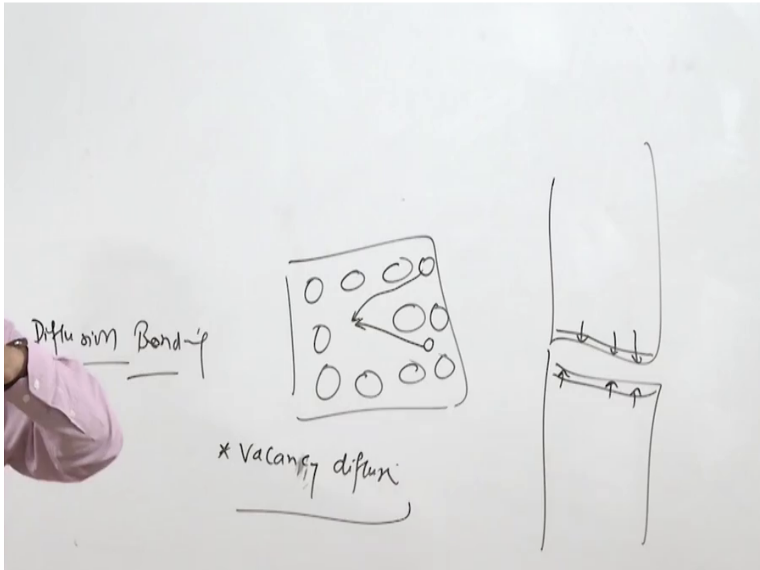
(Refer Slide Time: 08:26)



Initially contact is very localized here and there, but in the initial stage and when the pressure is applied, so the creep and the plastic deformation helps to have the metallic continuity now helps to have direct metal to metal contact and gradually in the grain when the diffusion starts all this contact area all this interface will be resulting wherever the metallic continue to exist in the grain boundaries are formed the like this but it is still some of the ores - pores are left here and there.

So grain boundary formation - grain boundary diffusion and the void shrinkage form means voids are left at the within the grains and subsequently continue diffusion volumetric diffusion helps in elimination of all these voids, but it takes a long time, diffusion occurs in a number of ways through the number of mechanisms.

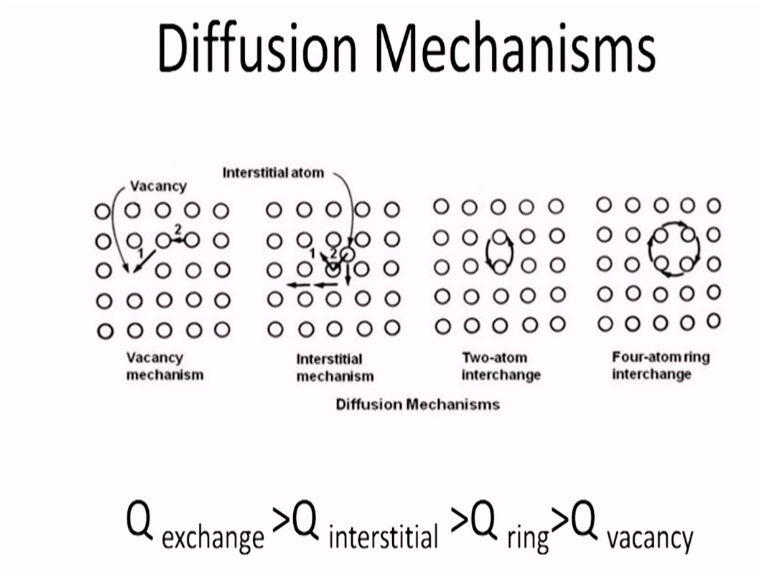
(Refer Slide Time: 09:26)



So what is needed for the diffusion to take place like - like this is the regular arrangement of the atoms, so if like say here it can be this is one if say this atom is missing then the - the small sized atoms can easily move this interstitial atom can easily move and fill this space or this atom can easily move and this and fill this space. So if in a metal system having large number of the vacancies near the surface layers.

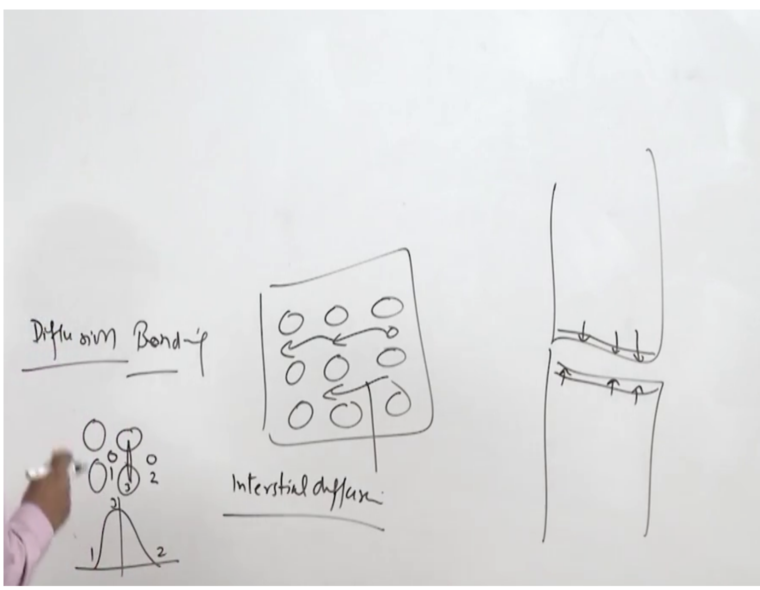
Then they will facilitate the diffusion at these vacancies especially near the interfaces so the vacancy diffusion is 1 - vacancy diffusion is 1 where the atoms occupy the vacancies and this happens especially when material is severely deformed vacancies and dislocations are created, so they will provide easily opportunity for the diffusion to take place through these vacancies.

(Refer Slide Time: 10:41)



So this is vacancy diffusion which has been explained here like the atoms move and they occupy the vacant spaces in the regular arrangement of the atoms and another one is the interstitial diffusion.

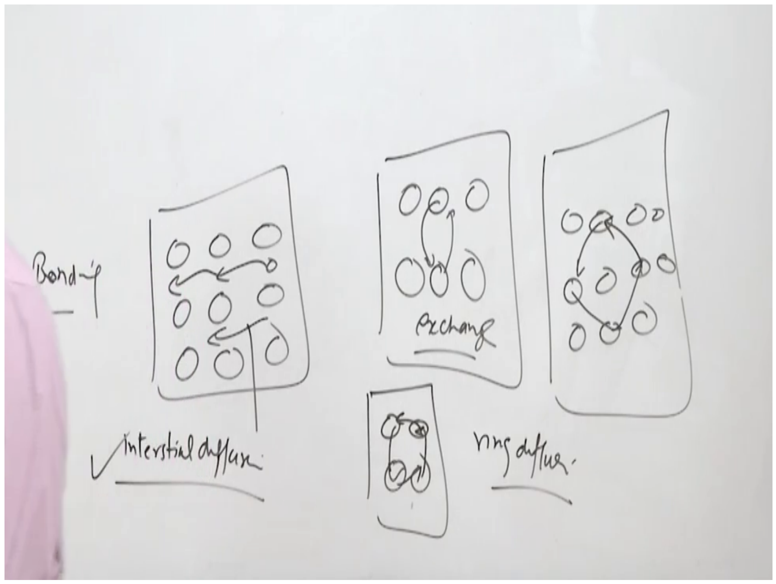
(Refer Slide Time: 10:58)



Where in interstitial diffusion if the atomic arrangement is regular and in this case if the atomic size is small it will moving from one place to another, and this is how the movement of the atoms take place things come closer to form the grain boundaries, so in case of the interstitial diffusion - interstitial diffusion we know that in regular arrangement like say if this is the regular arrangement of the atom so when one atom starts to move here.

So when it is in regular position it the stress energy associated with that is minimum, but when it reaches at the center the energy associated with this is maximum say 1, 2 and 3, so energy levels correspond to 1 and 2 or less and its maximum when it reaches in course of the diffusion at the center so amount of the energy is required for diffusion to take place will depend upon the way by which the diffusion is taking place. Let us say in case of the -

(Refer Slide Time: 12:15)

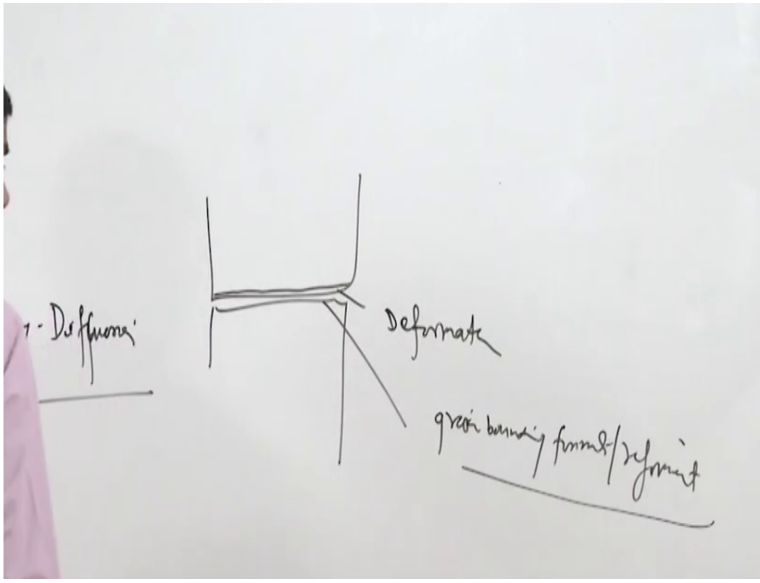


In one case, where the diffusion takes place through the exchange of atoms like this here, so these 2 atoms exchange their position or in one case where in regular arrangement of the atoms like this they change their position in particular fashion like this atom move is here, this atom move is here and like this atom goes here like this, so a ring kind of thing is formed as far as the change in their positions is concerned.

So here that the atoms change their positions like this and a ring kind of thing is formed, so this is called the ring diffusion, exchange diffusion, vacancy diffusion I have already explained and interstitial diffusion. So the - the kind of energy required for movement of the atoms through the different mechanisms is found to be the different vacancy diffusion needs the minimum energy for the movement of the atoms which is measured in terms of the activation energy.

So the activation energy is minimum for vacancy diffusion that is what we can see the first one ring diffusion is this one means so somewhat more amount of energy is required for the diffusion a ring diffusion, then interstitial diffusion and maximum for exchange diffusion, so depending upon the mechanisms involved the different amount of the energies are required for facilitating the diffusion.

(Refer Slide Time: 14:12)



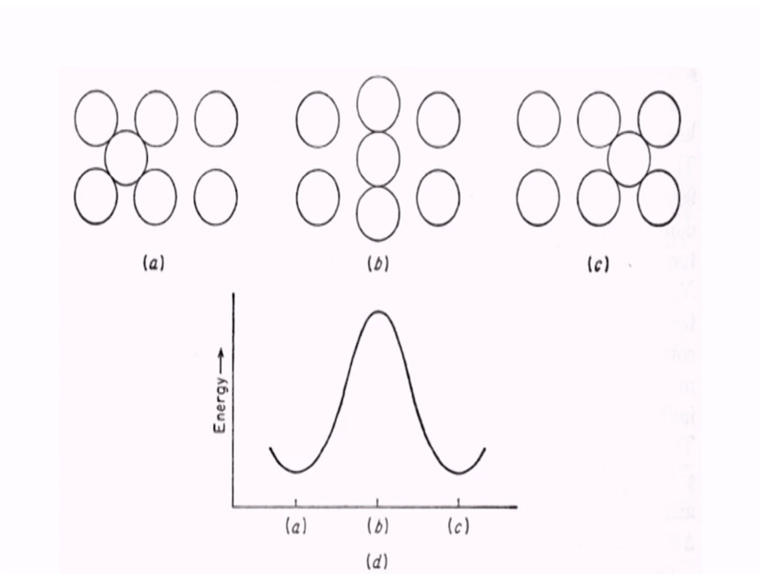
If we see this the vacancy diffusion - the vacancy diffusion needs minimum amount of the activation has offers needs the minimum activation energy while the exchange diffusion requires the - the maximum one, so to exploit this aspect what is done mostly efforts are made to have the more vacancies near the mating surfaces, so that the diffusion across the interface can be really facilitated.

So one of the approach related with this is that the surface near surface layers if they are deformed intentionally deformed in very localized manner, so controlled deformation of the surface layers of the two sides will help in - in two ways one is the grain - grain boundary formation through the refinement so means number the number of grains being formed that number of the grain boundaries will increase grain boundary area, will increase with the refinement of the grains.

So the grain boundary formation through the grain refinement and increasing the number of vacancies - increasing the number of vacancies through the deformation will further facilitate the diffusion and diffusion will also increase the dislocation density in the near surface layers, so this will further provide the opportunity - opportunities for the atoms to diffuse.

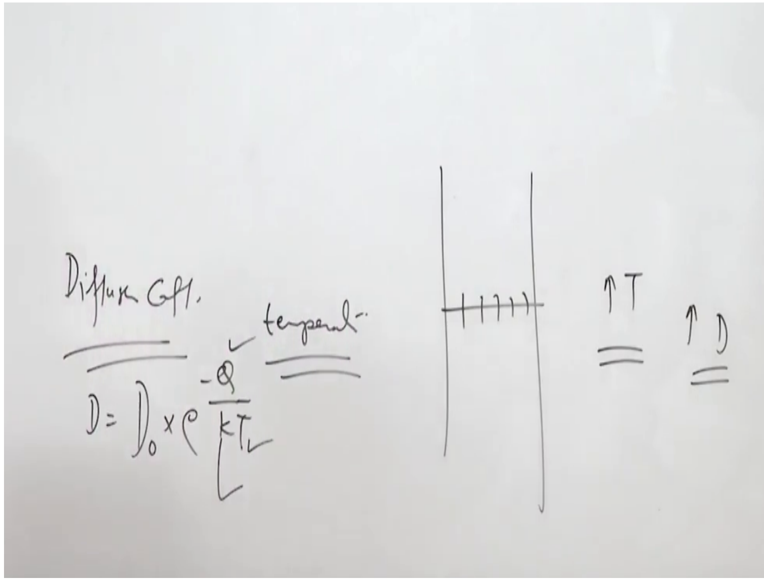
So this is one thing which can be done to have the near-surface layers which are more favorable from the diffusion point of view in very controlled ways refinement of the surface layers and the control surface layer deformation are the two things probably which can help in increasing the grain boundary help in the diffusion at the surfaces, so this is what I have already explained – explained.

(Refer Slide Time: 16:32)



When the atom is in its normal position energy level is minimum, but when as soon as it tries to cross the given the space between the 2 atoms energy level is high and then again it reaches to the - the lower level like say the c correspond to the position of the atom corresponding to the c energy level is minimum.

(Refer Slide Time: 16:56)

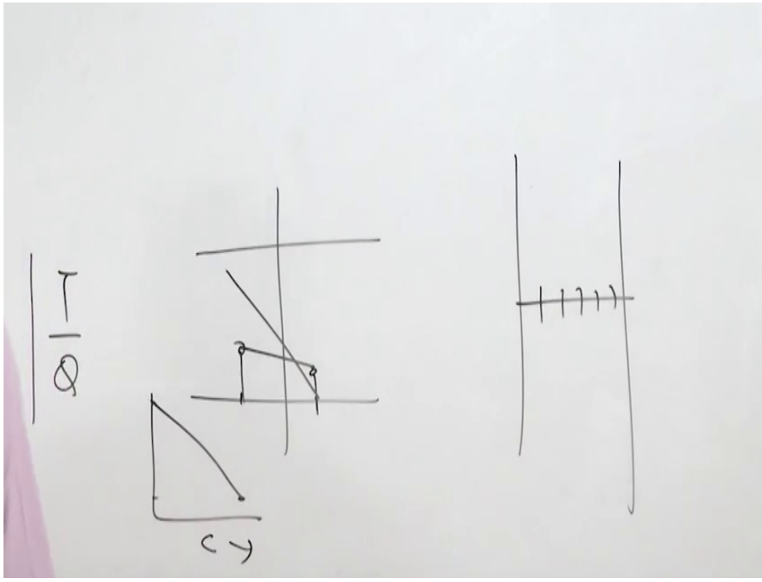


So now what distance how is at what is speed the diffusion will be taking place, so this is characterized in terms of the diffusion coefficient of the material, materials which diffuse faster will have the higher diffusion coefficient as compared to others for the different metal systems diffusion coefficient is found to be different and it is a found the function of the temperature and the metal systems significantly.

So in order to quantify or in order to express the way by which diffusion where is a diffusion since in the diffusion bonding diffusion is very crucial across the interface, faster the diffusion rapidly the bond will be created the or bond - bond will be established are formed between the components being joined, so it is important that diffusion coefficient is properly understood, so one is the diffusion constant and e raise to the power minus Q by KT.

So the activation energy is Q, K is Boltzmann constant, T is the absolute temperature so this equation reflects that it is the higher - higher is the temperature increase in temperature will be resulting in the higher diffusion coefficient and lower is the activation energy, higher will be the diffusion coefficient. So it is always good to have the low activation energy and the high temperature in order to facilitate the diffusion which is found to be the function of the material systems and the diffusion coefficient is also found the function of the temperature.

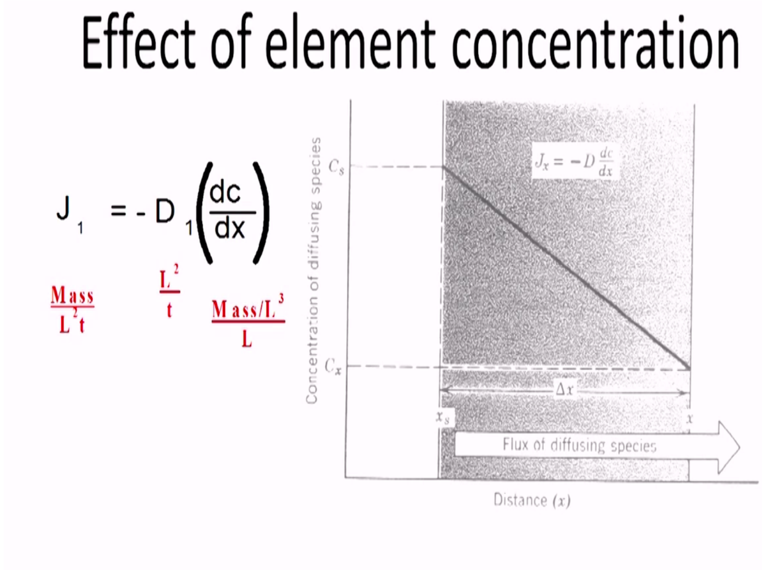
(Refer Slide Time: 18:54)



For given material how fast the diffusion will taking place - will be taking place apart from the activation energy and the D or the temperature if we see then it will depend upon the concentration gradient between the at the interface, so higher the concentration gradient of a particular element say if we say here the particular element concentration here its high and here its low, so the gradient can be shown like this.

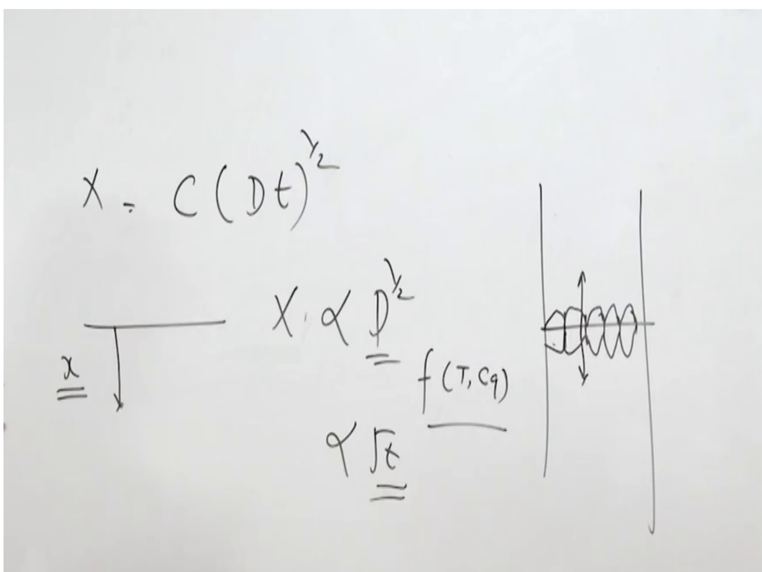
If the gradient is high the diffusion will be occurring at much faster rate it is just like the potential difference or the level in the fact the way by which the level between the two points go and the flow rate, so how is the concentration gradient between the two points like this, the concentration gradient is high for a particular element then diffusion will be faster if as compared to the case when the concentration gradient is less between the two points.

(Refer Slide Time: 20:06)



So this is what is expressed using this equation dc by dx indicating the concentration gradient between the two points, higher is the concentration gradient will be resulting in the much faster the diffusion as compared to the case when the diffusion concentration gradient is less.

(Refer Slide Time: 20:30)

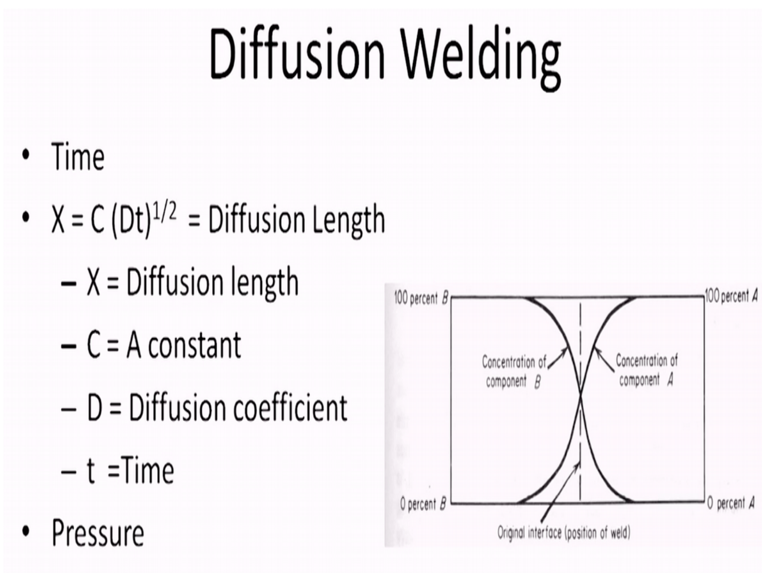


So another factor which will be determining the distance of to which diffusion will be taking place like this is the interface, so how for the things will be affected by the diffusion how for the new grain boundaries or the material will be affected metallurgically in course of the diffusion process that will depend upon on the conditions under which diffusion is taking place.

So if this is the interface this the distance up to which the diffusion will be occurring that is found the function of the certain things, so X is the extent of the diffusion length of extent up to which diffusion taking place, so this is found function of C (Dt) square root, so the distance up to which diffusion taking place is found proportional to the function of the diffusion coefficient which is of course the function of the t as well as the concentration gradient.

And on the other hand it is - it is also proportional to the square root of the t, so longer is the time greater with the distance up to which diffusion will be taking place as compared to the shorter periods, so this is what happens so X is the diffusion length is, C is the constant, D is the diffusion coefficient and t is the time.

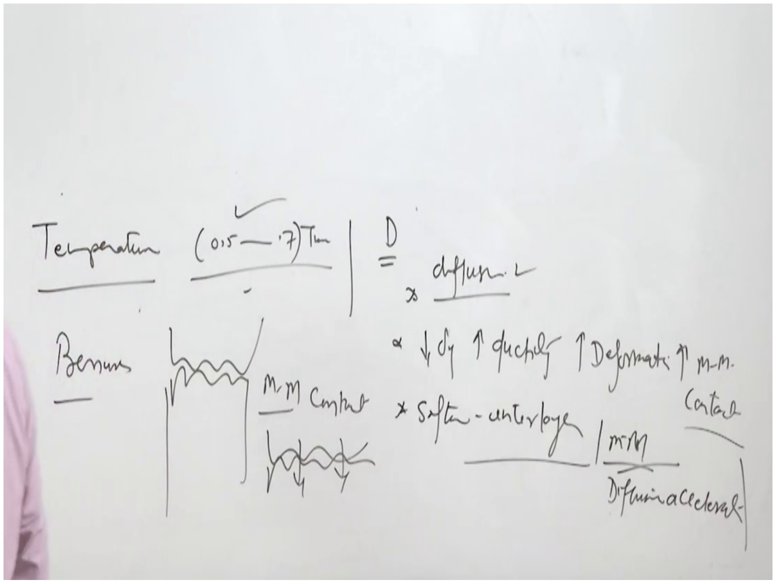
(Refer Slide Time: 21:56)



And whenever the across the interface diffusion takes place we will be seeing that there is a concentration gradient as for the elements. So element B will be diffusing towards the A and element A will be the diffusing towards the B and there will be continuous change in concentration of the elements in the two sides, so the distance up to which it will be happening the concern so of course this said - this says across the interface.

So concentration will be almost 50 50 if the things are completely diffusible in the two sides and then distance up to which is diffusion will be taking place this will be governed by the time and the diffusion coefficient of the material. So now we will see the - the important variables related with the process there are 4 variables which will govern the success of the process and these include.

(Refer Slide Time: 22:57)

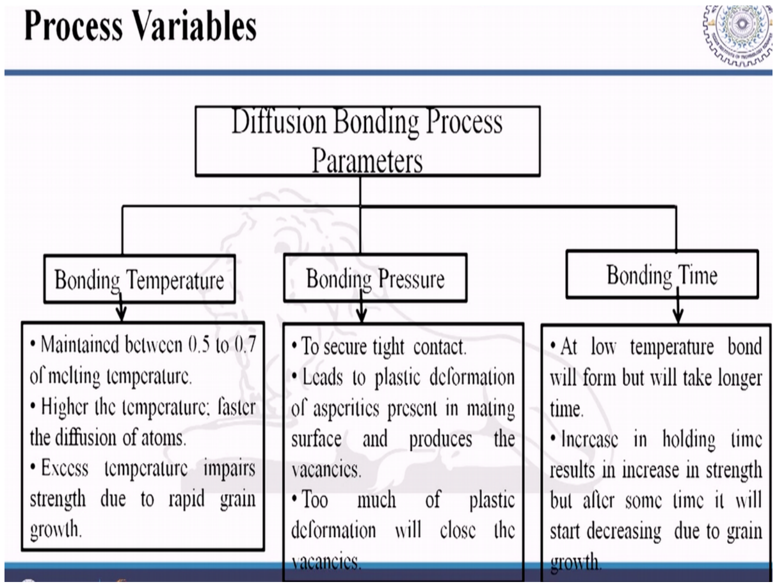


First is the temperature - temperature is very important normally it is kept 0.5 to 0.7 times of the melting point of the material in absolute temperature this directly governs the diffusion coefficient, so the diffusion is directly governed by the temperature so higher is the temperature higher will be the diffusion faster will be the diffusion bonding and the lesser will be the diffusion bonding time for a given strength.

So this is one thing apart from facilitating the diffusion it lowers the yield strength, increases the ductility of the material it helps in the surface layer deformation and increasing the metal to metal contact, so this is important for completing the initial stage and the diffusion is important for completing the second and third stage of the diffusion bonding.

It at the same time - at the same time it also helps to - it also helps to soften the interlayer if it is being used softening of the interlayers if it is being used to - to improve the metal to metal contact or to facilitate the diffusion, as a diffusion accelerator it can be used or it can be used just to have the better metal to metal connectivity between the members.

(Refer Slide Time: 24:42)



So as per diffusion bonding parameters are concerned bonding temperature it is maintained between 0.5 to 0.7 times, higher the temperature faster will be the diffusion of atoms which will be facilitate the diffusion bonding, excess temperature of course adversely affects because if the two high temperature is gap less is - is applied, then the coarsening of the grains in the base metal also starts and this kind of coarsening deteriorates the mechanical performance.

So increase in temperature within the reasonable limits of this range is good, but if it is kept too high then it will adversely affect the mechanical performance due to the grain growth of the material, the pressure is another important aspect that governs the success of the process, because pressure helps to collapse the peaks and valleys and increase the metal to metal contact this is one and it this is the important function.

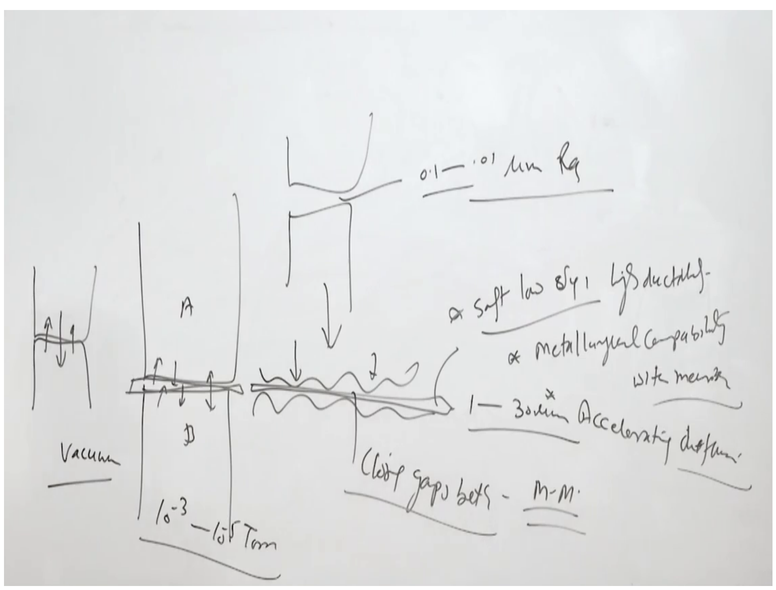
However once the complete metallic continuity is achieved then it does not play in course of the diffusion it does not play any role in course of the diffusion, so it helps to secure the tight contact leads to the plastic deformation of asperities present in the mating surfaces and helps to produce the vacancies due to the near surface layer deformation.

And the too much - too much deformation means excessive pressure sometimes deteriorates the mechanical - deteriorates the diffusions bonding process by reducing the number of vacancies this has been reported also that excessive deformation is not good because it closes the vacancies and it adversely affects the diffusion bonding process.

The time is another aspect it is good to keep it for long so that volumetric diffusion can eliminate all the vacancies all the sorry not vacancies all the pores which are present at the interface, but excessively large exposure time can lead to the coarsening of the grains so low temperature bond will form at the low temperature it will take longer time to develop the diffusion bond, because at high temperature faster diffusion - faster diffusion will facilitate the bonding earlier

Increase in holding time results in increasing strength but after sometime it will start decreasing due to the grain growth, we know that if the high temperature is kept for longer periods so then grain starts to grow and that adversely affects the mechanical performance and since the diffusion bonding is carried out at high temperature more than half of the melting point, so adversely - it adversely affects the diffusion bonding process.

(Refer Slide Time: 27:38)



So now we will see, the sometimes interlayer is intentionally used or like say the 2 components A and B are to be joined, so one purpose of using the interlayer like if the surface is really too rough then use of the interlayer which is normally thin maybe 0.5 sorry maybe like 1 micron to 30 micrometer thickness is normally used this interlayer is normally soft low yield strength and high ductility, these are the important features from the mechanical point of view.

And metallurgical compatibility - metallurgical compatibility with the members being joined is the another requirement sometimes it also you helps in accelerating the diffusion - accelerating diffusion across the interface, so these are the three purposes which are basically achieved if the A and B are not compatible with each other then let us have the third layer which may have the compatibility with both so the joint is formed.

Another is this presents of this interlayer can help in accelerating the diffusion across the interface so the bond is formed quickly, third is the presence of the soft low yield strength, high ductility interlayer under the pressure will be getting deformed following the path of the peaks and valleys and so closing the gaps between - closing the gaps between the peaks and valleys and increasing the metal to metal contacts.

So these are the three functions which are normally achieved with the help of with the use of the interlayer, so in improving the metallurgical compatibility metallic intimacy and the diffusion accelerators, so normally it should be soft low yield strength and high ductility, these are normally thin layers may be used in form of seats or in form of powders or these are normally metal systems like nickel, copper, silver, gold etc. are the commonly used interlayers.

And this is typically bond which is showing the two components joint using the silver interlayer showing that how the interlayer appears when the diffusion bond is developed using the interlayers and this is the typical system which is used for developing the diffusion bond we can say it is a vacuum hot press where this control chamber and this is the main vacuum chamber with the heating capability using the resistance heating principle.

And it is a ten-ton capacity press and the samples are kept this is the vacuum chamber and hear the samples are kept under pressure and the diffusion suitable vacuum selected.

(Refer Slide Time: 31:02)

So that impurities are not formed at the interface in presence of the gases and so this is the typical system which is used for developing the diffusion bond, there can be variety of systems of this similar kind. The vacuum is another parameter which is which should be discussed like vacuum will be facilitating the absence of the atmospheric gases so vacuum of 10 to the power minus 3, 10 to the power minus 5 torque is commonly used.

When this vacuum is used all the gases are taken up from the vacuum chamber and so the metal surfaces which were prepared preparation is important normally 0.1 to maybe say 0.01 micrometer roughness is prepared this must be cleaned from all the impurities and the traces which may be there at the surface. So that when they are the surface - the smooth clean surfaces are brought in contact.

In vacuum, they the direct metal to metal contact exist at high temperature and under pressure across the interface diffusion takes place and the bond is developed. Now I will summarize this presentation in this presentation I have talked about the fundamental mechanisms which are involved in diffusion and the way by important parameters related to the diffusion bonding and what is the role of the vacuum, what is the role of the inter layers.

And what are the factors that matter for development of the diffusion bond, what is the need what kind of systems are which are normally joint using the diffusion bonding, thank you for your attention.