Mathematical Modeling of Manufacturing Processes
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Lecture - 34
Evaluation of Microstructural Properties and Residual Stress

Hello everybody. We have already discussed the different heat treatment processes normally used in case of any manufacturing processes and of course most of the cases, after following some kind of manufacturing process to get a product normally we follow any kind of heat treatment, but I will try to discuss that how different heat treatment process is associated with the different types of the manufacturing processes.

But in general I will try to look into that that evaluation of the microstructure properties and of course residual stress how to influence of the different manufacturing processes that is the main coverage for this part of this module. So we start with that different manufacturing processes. First machining process.

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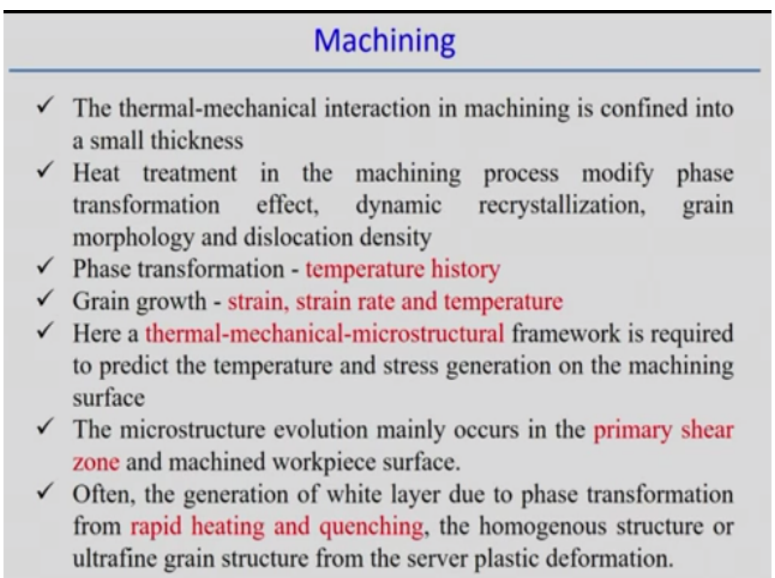

We know the machining process, the machine surface is actually on the top surface and very thin layer that is affected due to the formation of the cutting process and that in microstructural point of view it is actually affected by the high rate of the strain rate, high deformation and temperature that is the main driving force to alter the microstructure property on the surface.

Now we try to improve the surface properties and just by application of the heat treatment processes, even in case of machining process.

So of course in machining process, there must be some thermal mechanical interaction, and that interaction is actually confined to not the whole domain of the work piece, probably we can say the very thin layer of the work piece and maybe we can say that up to the extent of the what is the thickness of the chip normally we generate up to that point, maybe this thermomechanical interaction normally happens during this process.

So of course in machining process we follow different types of the heat treatment processes and that actually modify the phase transformation effect, actually influence the phase transformation dynamic recrystalization process, grain morphology and of course the heat also alters the dislocation density. So in general, in machine surface we normally characterize from the materials point of view that in terms of the standard strain and temperature.

So in that cases, probably we can relate what are these strain standard and temperature of whatever heat influence to form recrystalization in the case of machine surface. Of course, if you look into the high speed machining process. In that cases there is a rapid transformation of the heat normally happens in this case. So the mechanism can be different in these cases probably we can say the activating, maybe during this process, there may not be any transfer of the heat from the domain.

So we can say it is activating process, so in this case this normally form the safe band in machining processes. So of course, we can modify the surface by using the heat treatment processes. So in this case, the phase transformation happens from the machine surface that is mostly influenced by the temperature history and then grain growth is actually influenced by strain standard and of course temperature.

But of course in these cases also we need to consider the thermal mechanical and microstructure premark to understand the required temperature and the stress generation on it on a particular machining surface. So here also we can follow kind of the thermomechanical analysis, but the microstructure evaluation normally happens, mainly happens due to the primary shear deformation and on the machine work piece surface.

But sometimes, we observe in the machining surface some white layer and that white layer is maybe due to the phase transformation and that rapid heating and quenching is normally followed because in this case the rapid heating during the machining processes, if the machining speed is very high and quenching means if you use some kind of the cutting fluid. So that is actually acts to quench surface of course. So therefore the structure can be different.

So most of the cases, we can find out some kind of the white layer. So therefore the homogeneous structure are the ultrafine grain structure may be possible and because of the high severe plastic deformation happens on the surface. So apart from that, of course that is the machine surface. So sometimes the machine tool also is subject to some kind of heat treatment process to improve the properties of the machine tool.

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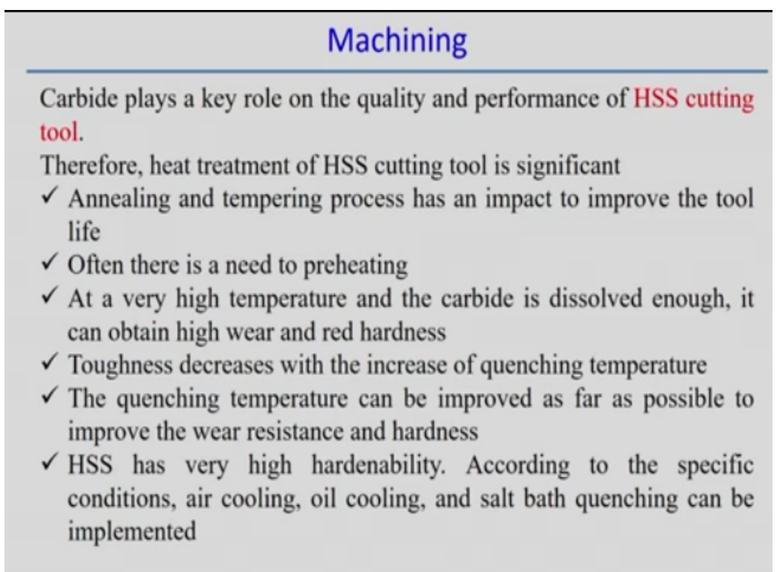

Maybe if you consider the carbide tool, in this case the formation of the carbide, their size, their distribution, the surface of the carbide, whether it is smooth or rough surface. Heat actually influences the properties of the high speed cutting stool. So in cases, we can see that of course we normally follow the different heat treatment technology in case of HSS cutting tool and which is also important to analyse in these cases.

So normally, annealing and then tempering process has an impact to improve the tool life of the HSS tool. So often there is a need of the preheating. So before doing the heat treatment, we normally preheat the sample from where we are suppose to make the cutting tool. Therefore, at a very high temperature, if we follow high temperature, normally the carbide is about to dissolve mostly, about to dissolve enough.

So therefore heat actually impart kind of the hot hardness properties and heat can obtain very wear properties and red hardness properties and that is also very important in case of a cutting tool material, but toughness decreases with the increase of the quenching temperature. So at which temperature we are doing the quenching process, so the toughness depends on that actually. So it is like that only.

So probably if in case of quenching temperature, so quenching temperature, if it is very high temperature, then we follow very rapid cooling, probably in the case of martensitic structure will be more. So in that sense, the materials become more harder, but with the compromise of the toughness of the material may be poor in this case. So therefore quenching temperature is having some role to decide the toughness of a particular material and of course this actually, in what way it depends on that.

It is from the hard carbide, so whatever you distribute the hard carbide, it forms distribution, that decides the toughness and maybe hardness of a particular components. So therefore if the quenching temperature can be improved as far as possible to improve the wear resistance and the hardness of both can be improved in these cases, but if we follow the tempering process only, then we can impart some, we can bring some kind of the hardness.

So in that cases, probably the distribution of the maybe carbides can be improved, if we follow the tempering process and normally do these things. So that is why we normally perform the annealing or any other heat treatment process, quenching. Quenching normally if you do the quenching process after that, we can follow the tempering process as well to make a balance properties of a particular tool.

Balance means in the term of the hardness strength as well as the toughness of the material. So HSS having very high hardenability, so therefore, according to the specific conditions, we can follow in the different medium for the quenching normally we know that air cooling, wire cooling and solid path we normally follow. The difference is that in different cooling medium we follow that rate of the cooling can be different in all these cases.

And in all these cases maybe heat, the properties can be different depending upon what way the carbide forms the size of the carbide and the distribution of the carbide in case of heat treatment of HSS cutting tool. Now we try to look into the powder metallurgy product. So even it is also, even powder metallurgy product we can follow the heat treatment processes, but of course in certain processes can be done even powder metallurgy product that most significant important step is the sintering process.

So in sintering process can be done carefully probably that can act sometime as a substitute for the heat treatment process, but still if we want to fine tuning of the properties, accuracy of the properties if want to improve, in that cases, we normally follow the heat treatment process after doing that in the powder metallurgy product. So therefore the properties of the powder metallurgy products are mainly determined by the alloy used and the sintering process are followed.

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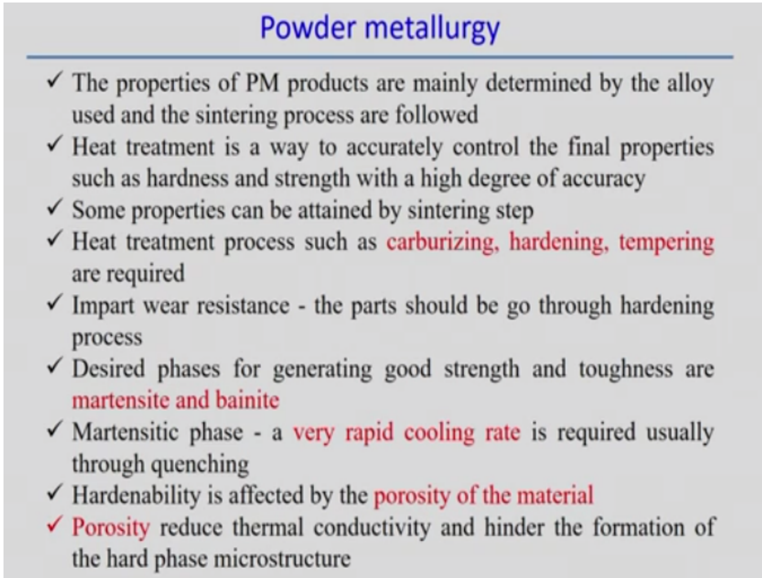

So what kind of the alloy combination we are using and what sintering process the temperature and all these things were following, mostly the properties is decided by this in this step actually, but of course heat treatment also we can follow, but it is a way to accurately control the final properties, or we can say fine tuning of the properties such as combination of the hardness, strength, and toughness up to high degree of accuracy, we can control using the heat treatment process.

So therefore, it is also necessary to follow the heat treatment process even for the powder metallurgy product. So some properties can be attained by sintering step that I already mentioned that even some significant properties can be achieved by simply following the heat sintering step, but apart from that further if you want to improve the properties, then we can follow the kind of heat treatment process.

Normally, the heat treatment processes are just carburizing, hardening, and tempering, is followed in case of the powder metallurgy product. So in powder metallurgy product, for example imparts the wear resistance. So in this case, if you want to impart the wear resistance, then parts would go through the hardening process. So if you impart any kind of, any particular zone to impart the wear resistance properties, so that part would go through the hardening treatment process.

And if we desire phase for generating the good strength and toughness normally in the steel, that is martensite and formation of the martensite and the bainite. So that actually presence of martensite and bainite phase actually impart, brings the considerable good amount of the strength and toughness in case of the powder metallurgy product, but of course we know that martensite, if you have to produce the martensitic.

Then very rapid cooling is normally follow to produce the martensitic phase and of course if you create the martensitic phase, quenching process, then it is also necessary to follow some kind of the tempering process. So that rapid cooling, if we follow some rapid cooling process, so that is called the quenching process and that is what we can say it is actually achieved through the quenching process in a powder metallurgy product.

But the difficulties when using powder metallurgy product is that presence of the porosity in this product. That is the one serious, maybe draw back in powder metallurgy product, is the maybe possibility, high possibility of formation of kind of porosity. So therefore, if we impart brings the hardness, then porosity creates the obstacle to impart the up to certain extent brings the hardness through even if you follow, very accurately the heat treatment process.

Then may not be possible because of presence of some kind of the porosity within the material. So that is one issue, because porosity if you want to follow heat treatment or if we are applying the kind of the heating to the surface, then porosity actually influences or maybe retard the heat convection, disturb the heat convection or maybe we can say that reduces thermal conductivity of a particular material with presence of these things.

At the same time, it also, presence of porosity also hinders the formation of the very hard phase microstructures that porosity creases the obstacles to form the hard microstructure up to certain depth in a porous structure. So that is the one difficulty of the powder metallurgy product even application of the heat treatment process. So in generally its presence, if we handle the steel material, then the presence of cobalt sometimes promote the formation of the pearlite and formation and decreases the ferrite content.

But of course, overall hardness can be increased in presence of the copper, but hardness can be improved up to certain extent, up to optimum level of the addition of the composition of the copper. So some copper can be added up to certain extent, up to optimum level such that we can impart the hardness in powder metallurgy product also.

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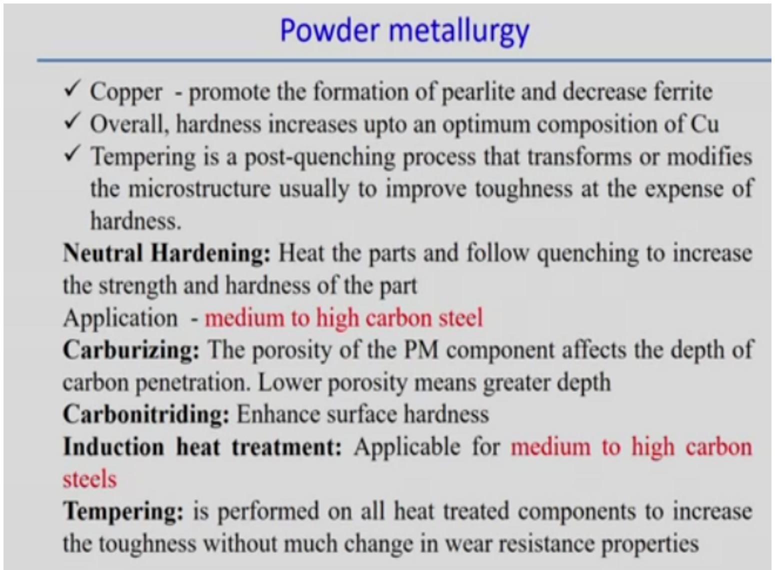

So of course even if you follow, if you create most of the cases we normally follow the tempering process and of course, this tempering process is the kind of the forced quenching process. So most in general, following the quenching process we normally follow the tempering process or of course tempering process is relatively low temperature and maximum temperature raise relatively low as compared to the other heat treatment processes.

But tempering creates some kind of the balance that transforms or modifies the microstructure, see in such way that it actually improves the toughness, but of course at the expense of the hardness at the same time, maybe it more or less brings some distribution of some particles uniformity if you are following the tempering process. So properties tempering process all the kind of properties, chemical properties it tries to distribute uniformly throughout the structure.

In powder metallurgy product, we follow the different kind of the heat treatment processes, we can see the natural hardening. We say simply heating the parts and up to certain extent, up to certain temperature keep it for sufficient time, then it is followed by quenching to increase the strength and the hardness of the part. So simply natural hardening, we can simply heat under normal atmosphere and then heating and quenching can be followed.

So in that case, once you follow the quenching process, then the purpose is to impart the hardness to the component. So of course the natural hardening is, we can follow the application to normally, medium to high carbon steel. So medium to high carbon steel, there is chances of wide variability in the formation of the presence of the carbon, so that carbides and their distribution is basically taking part that influences the properties, which normally bring the heat treatment processes.

So that is why it is more applicable for the medium to high carbon steel. So if carbon percent is very low, almost very low carbon steel definitely formation of the carbide maybe not as much influential during the heat treatment process like medium and high carbon steel. So in this case, that is why this applicability of the natural hardening are mostly restricted to the medium to the high carbon steel.

Similarly carburizing we understand if you want to bring the impart more carbon to the surface and that actually forms the carbides in powder metallurgy product. So therefore, to bring the component in the involvement of a carbon so that carbon can be deposited in the form of carbide within this component. That is we have already discussed, that is the carburizing processes and that is one heat treatment and normally impart the surface hardness following the carburizing process.

Of course, porosity of the powder metallurgy component affects the depth of the carbon penetration, because it depends on that. Lower porosity means greater depth, if porosity is very high, then hardening depth can be restricted to very small, but if porosity is very low, hardening depth can be increased, can go for a high depth. So therefore, it depends on the powder metallurgy for which to what depth the carburizing can also happen.

Carbonitriding, we understand the carbonitriding means imparting the carbon and nitrogen to the components in the form of carbides and nitrides that impart brings hardness to the components.

So of course this carbonitriding is, simply the purpose is to bring the, enhance the surface hardness of a particular component and of course in this case is powder metallurgy component. Sometimes, induction heat treatment can also be done in case of the medium to the high carbon steel to bring the hardness properties of a powder metallurgy product.

So apart from the tempering, this is also followed in case of powder metallurgy component, which is performed all heat treatment components to increase the toughness without much change in the wear resistance properties, actually without much change in the hardness properties or wear resistant properties, it brings the toughness or enhances the toughness of a particular component.

So therefore, all powder metallurgy product finally we can follow the tempering process, such that it actually makes the balance between the toughness and imparted hardness properties of a particular component and it is also try for the powder metallurgy product.

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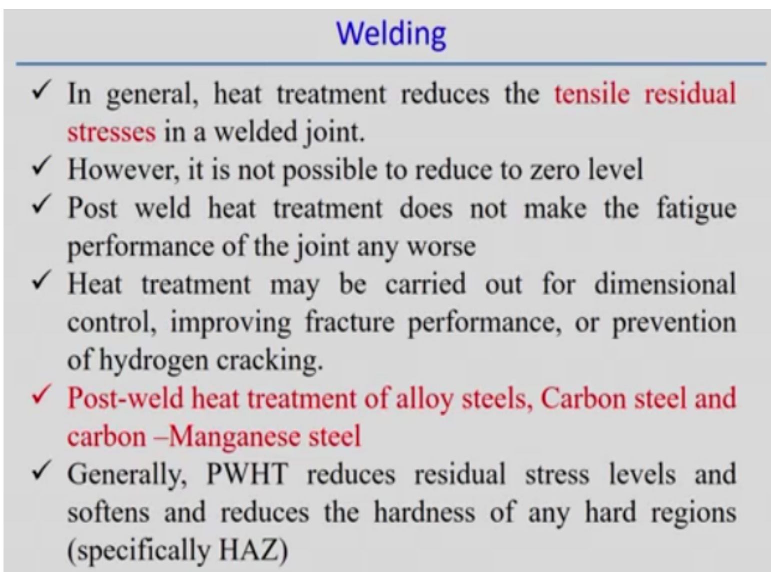

Now apart from powder metallurgy, we can look into the welding process also, already a little bit we have discussed in the last module, that different heat treatment process and relates the different kind of the welding process, what welding process, in which welding process, what type of heat treatment process normally followed, or maybe if we follow the heat treatment process, what kind of improvement we can follow in welding structure.

Little bit we have discussed, but here also specific things and specific welding process in general, the heat treatment reduces the residual stress in a welded structure. If we follow the heat treatment process, it reduces the residual structure, but of course, it is also necessary to mention that compressible, residual stress in earlier structure is to some extent beneficial, but tensile residual stress may not be beneficial in welding structure.

So the objective of application of the heat treatment process in our lead structure actually to modify the, to reduce the residual stress formation n an welded structure, but it is not possible to reduce the residual stress to bring it to 0 level, even whatever post-weld we can apply the heat treatment process in our lead structure. So some, we can just reduce it up to certain extent.

So therefore, post-weld heat treatment most of the cases, welding processes is associated with the post-weld heat treatment process to make the, or maybe we can say in general to modify the microstructure as well as to reduce the residual stress generation and when there is a reduction of the residual stress, there is normally the fatigue properties of a welded structure can be enhanced or improved.

Therefore, heat treatment can be carried out for dimensional control improving the fracture performance or prevention of the hydrogen cracking, that is also other purpose of doing the heat treatment in a welded structure, but of course if we try to look overall the post-weld heat treatment of different carbon steel, different alloy steel or carbon-manganese steel, that kind of steel if you look into the critical points relevant to different types of the steel and if we apply the heat treatment in a welded structure.

Generally post-weld heat treatment reduces the residual stress level and of course its occurrence and reduces the hardness of any hard zone, specifically the heat affected zone, it becomes shorter with the application of the post-weld heat treatment process in a welded structure.

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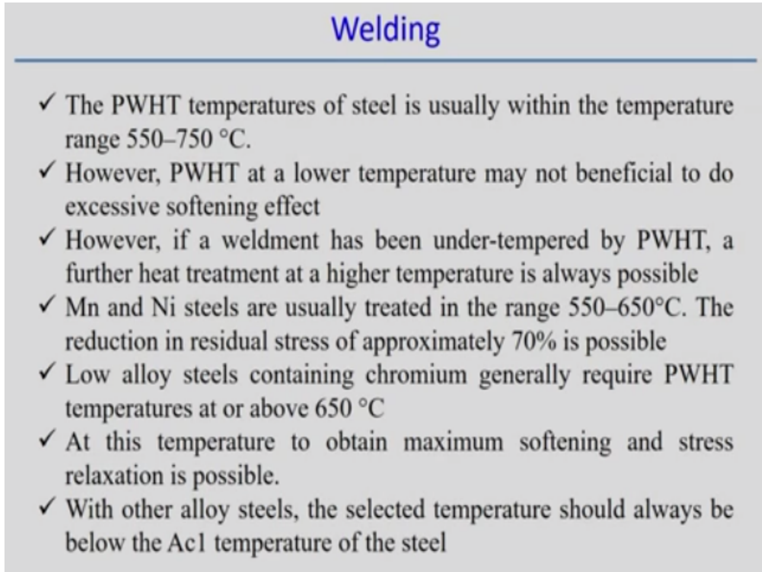

But apart from that the post-weld heat treatment temperature of steel is usually normally is performed between the 550-750 degree centigrade for most of the steels, but of course in this case, the post-weld heat treatment is the lower temperature, sometimes it is not beneficial to do the excessive softening of the, to bring the excessive softening effect through the heat treatment processes and there is some limitation up to that point.

We can bring the softness effect in the welded structure through the heat treatment process, but of course this softening effect normally brings to bring the post-weld heat treatment towards the lower temperature. Of course, there may be some metallurgical phenomena if you analyze correctly and then probably we will be able to understand the different types of the structure, to what temperature we need to go for the heat treatment process, such that we can bring the maximum softness of any kind of welded structure.

Of course if we do the welding under temper, if it has been under temper by post-weld heat treatment processes. In this case, further heat treatment is possible and that further heat treatment at high temperature, it is always possible to modify the structure further. So therefore, actually tempering is normally done as we can say that the lowest temperature as compared to the other heat treatment processes and that at the lowest temperature, just to make the balance harder to relate by compromising the hardness of a particular material.

Such that you can bring little bit softness, bring some ductility properties and toughness and through the tempering process. That is why tempering process is normally done at relatively low temperature. But if you look into the nickel-based steel, they are usually treated in the range of 550-650 degree centigrade and the reduction in the residual stress of approximately 70% is possible.

So if you follow that looking into a microstructural phenomena of steel and accordingly we can raise the temperature, we can perform the heat treatment process up to certain temperature and of course, this information, we can get from the phase diagram TT or CCT diagram and that it is possible in a design the heat treatment process in such way that even around approximately 70% of the residual stress is possible to reduce through the heat treatment process of steel in a welded structure.

If you look low alloy steel containing normally chromium, generally post-weld heat treatment will be at a high temperature and that is above 650 degree centigrade, because at this temperature it brings a maximum softness and the stress relaxation is possible. So therefore, we can get actually this information, whether it is 650 degree centigrade or 600 degree centigrade or 550 degree centigrade, then we have to go through in details in the phase transformation diagram looking into different phases formation at which temperature.

That is important to know to design the heat treatment process of a particular steel, or a particular product. Even when the other alloy steel, if we look into the other kind of the alloy steel, the selected temperature should always be below the Ac1 that means one critical temperature normally in case of steel, if you look into the phase diagram, it is around 727 degree centigrade. So we can perform the heat treatment process below this temperature and in case of the other kind of the alloy steel.

So that is why different composition, the same heat treatment process, but that treatment process can be designed at the different temperature to get the maximum benefit through the heat treatment process. Maximum benefit means maximum possible reduction of the residual stress or maximum possible to bring the relaxation of the stress or maximum possible to bring the softness without much compromising with the decrement of the hotness by following kind of the heat treatment process.

Now apart from the welding processes also we can do heat treatment following in the case of the metal hardening process and even this metal forming process is sometimes designed to perform the heat treatment process intermediately. Even we have discussed that even some kind, in some drawing processes, we can perform the heat treatment process intermittently.

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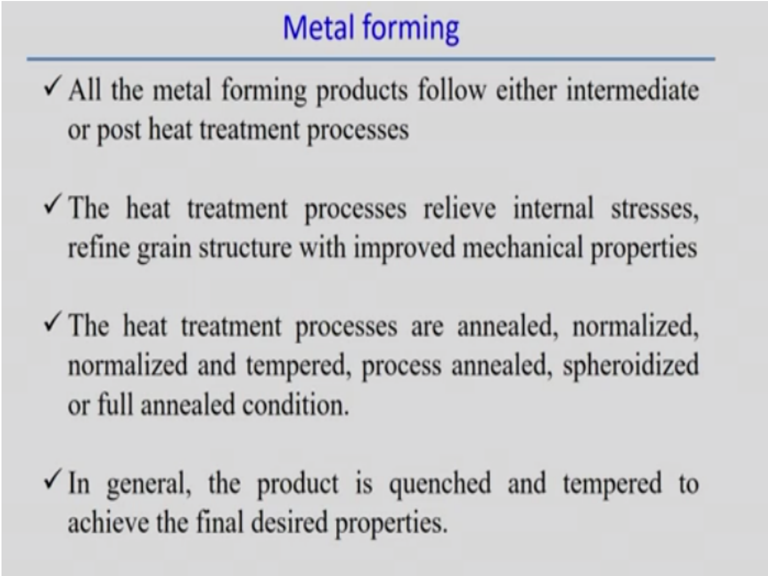

But apart from that all the metal forming products definitely it follows some kind of either intermediate of the post heat treatment processes to bring or improve the mechanical properties or microstructural properties of a forced component or maybe the component net followed by some kind of the metal forming processes. So therefore, in general the heat treatment processes relieve the internal stresses.

Heat actually refines the grain structure with improved mechanical properties, of course and there is, when it improves the internal stress and refines the grain structure, then the mechanical properties actually alters. So most of the cases, mechanical properties altered in the sense that it changes the strength and ductility and of course toughness also altered through the heat treatment processes.

So now in metal forming, the heat treatment processes are normally combining the single heat treatment process or combining of the 2 different heat treatment processes that normally follow. For example, in case of metal forming, normally annealing can be done normalizing and of course sometimes normalizing and tempering can also be followed and in certain cases process annealing can also be followed and speroidization and full annealing condition can also be followed.

So of course what type of the heat treatment process is normally followed, so to some extent we can restrict what is the carbon percentage in the steel and we already discussed that low carbon steel or the high carbon steel, what type of heat treatment process, we normally follow and what type of process is basically faster and what type of process is relatively very slower process. So if slower heat treatment process, we can say in terms of the cost, it is a little bit costly as compared to the low time required to perform the heat treatment process.

So therefore, in general apart from all the heat treatment process, it is very quick process to modify quickly the properties of a manufacture component just simply following the quenching and tempering process and that by carefully controlling the quenching and tempering process, it is possible to bring desired properties of a manufacturing component and of course it is metal forming process, we normally follow the combination of the quenching and tempering process.

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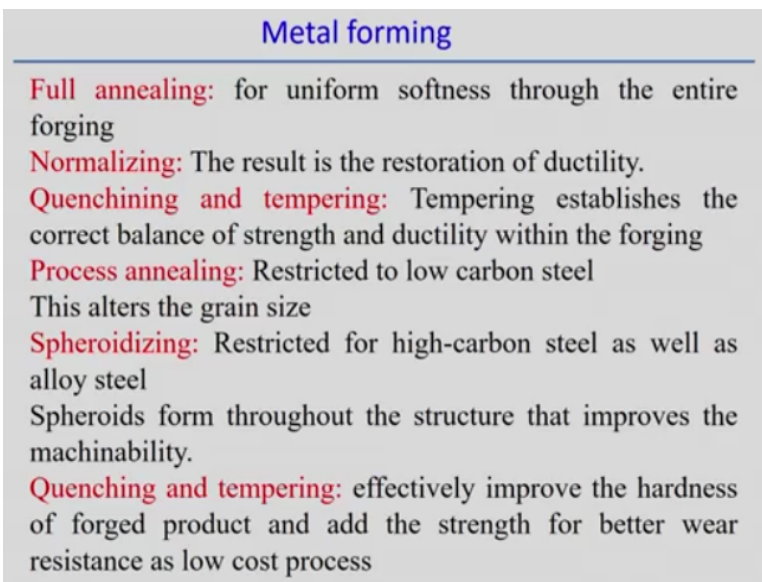

But apart from that, we look into the full annealing process and of course in metal forming process, if you follow the after forge component is for example, if we follow in these cases, we perform the full annealing process such that it brings uniform softness throughout the entire forging part. So that is how you can bring the full annealing process. So of course full annealing process is a relatively slow process.

Because in these cases we follow the harness cooling, which the cooling rate is very slow process, so it takes much more time. We can follow the normalizing process, for this normalizing the result is the restoration of the ductility. It can restore the ductility of a particular product, because in a forged product, we normally in forged product, if you do some of the mechanical working on this particular component, the metal becomes still hardened.

So if you follow any kind of the metal forming process, after that if we evaluate the properties most of the cases, then the ductility normally reduces. So if you want impart the ductility, if you want to bring, restore the ductility, then normalizing process can be followed in a forged component and quenching, tempering, just following the quenching process and after following quenching and then we can follow the tempering process that make the balance of the strength and ductility within the forging component.

That is normally done. Then process annealing can also be done and it is restricted to low carbon steel and of course this alters mainly the grain sizing if you follow the process annealing process in a metal forming component. Spheroidization also is restricted to high carbon stool, it normally forms the spherical shape of the carbides and that actually imparts, changes the properties of the product.

So spheroid is formed throughout the structure, that improves the machinability throughout. Actually it improves, if spheroidizing, if you follow the heat treatment process finally it actually improves the machinability properties of a particular component. Even quenching and tempering also here already mentioned, there also quenching and tempering also effectively improve the hardness of the forged product and adds strength for better wear resistance and low cost process.

Actually, we are making the balance, that is the main purpose of the quenching and tempering process at the same time. We can add the strength if you follow the quenching process, we can add the strength for the better wire resistance properties and it is also low cost process, and along with the tempering process, we can restore properties, or we can bring the toughness, restore the properties means we can normally bring the toughness and the ductility of a forged component.

So therefore, integration apart from this individual different heat treatment process is normally following the metal forming component.

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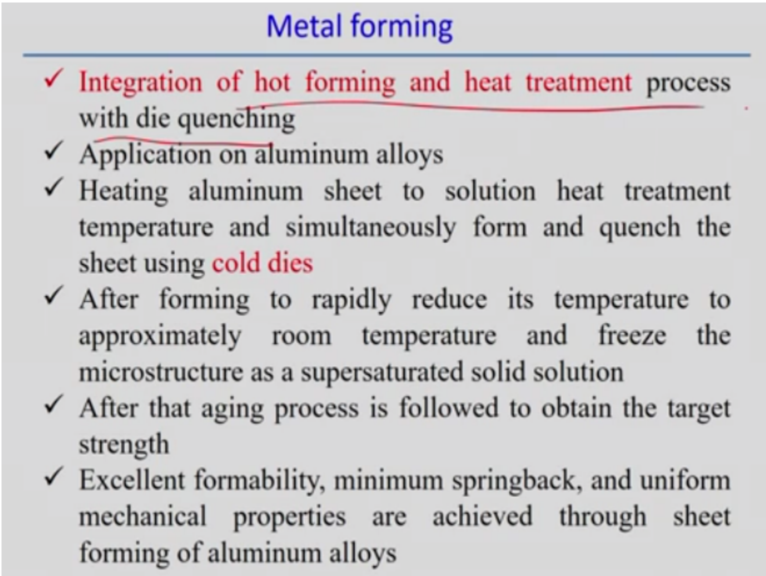

So it is nowadays the integration of the hot forming and heat treatment process can also be integrated with the die quenching is also developed. So in this case, the metal forming process and that different heat treatment process with the die quenching is merged and we integrating this we can develop a process and normally it is applicable in case of aluminum alloy. So what it works? In principle, the heating of the aluminum to the solution heat treatment temperature.

Solution heat treatment temperature makes the solution at that particular temperature and of course at the same time we can keep the time to bring that particular solution, then we can simultaneously follow the quenching process, but that quenching process we follow using the cold die. So cold die is the controlled temperature and the cold die is responsible for the quenching of a particular rate of the temperature, temperature change in this case.

So in this process, after forming definitely for the quenching process that is actually associated with the rapid reduces the temperature with the interaction of the cold die and approximately it brings to the room temperature and freeze of the microstructure at the supersaturated solid solution. So when you follow the quenching process, it is a rapid process. So what was the microstructure in the solution during the solution treatment at the temperature, that can be preserved if you follow the quenching process.

That means, other way we can say if you follow the rapid cooling, then we can preserve that microstructure that is called, of course it creates a supersaturated solid solution it forms. Then, when you form supersaturated solid solution, after that if you follow some aging treatment normally it is non-ferrous alloy, the strengthening mechanism is more following the etching treatment.

So therefore if you follow the etching process to obtain the target strength and this is one kind of heat treatment process if you follow it up. In this case, excellent formability, minimum springback, and uniform mechanical combing all these properties are achieved through sheet forming of the aluminium alloy. Actually by integration of the heat treatment and forming processes, the purpose to bring all the different properties together.

Such that we can make a good product by combing all these processes and of course just to avoid so many different types of heat treatment process individually. By even casting component also follow some kind of the heat treatment process.

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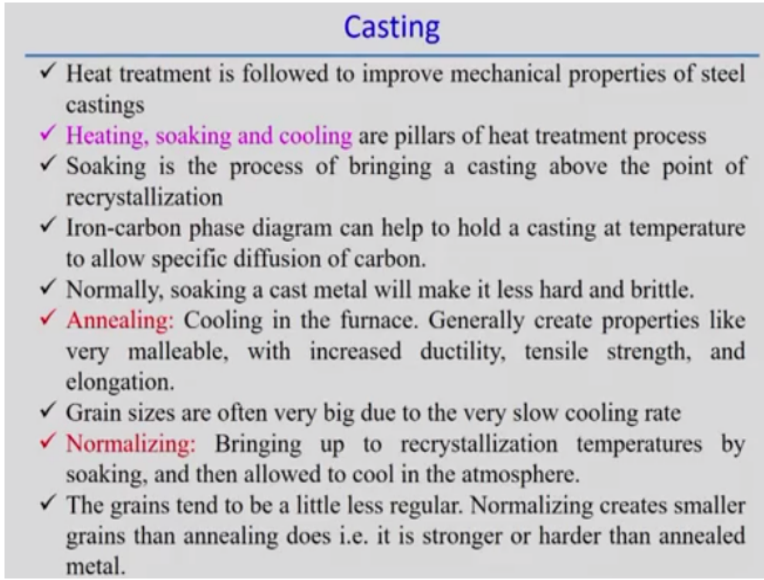

In these cases, the heat treatment is followed to improve the mechanical properties of the steel castings. So normally, we understand the heating, soaking and the cooling are the main part of any kind of heat treatment process. So heating means, we can heat the sample up to desired temperature and soaking means we keep sufficient time that means during this period, we allow some diffusion and then after that we follow some kind of the cooling process with a predefined cooling rate.

So therefore, these are the steps in the heat treatment process. So soaking is the process to bring in the casting above the point of recrystalization. That means, we can bring sufficient time at this temperature, such that recrystalization allows recrystalization to happen. So if we look into the iron-carbon phase diagram also that can help to bring the casting to hold the casting at a temperature of a particular time, such that diffusion of the carbon may also happen.

Diffusion of the carbon and microstructural changes may happen at this process. Normally, soaking of the cast metal will make it less hard and brittle and in this case if allow much more time, we can allow the diffusion of the carbon during this process normally try to reduce the hardness and brittleness. Of course in casting product also we follow the annealing process, normally annealing process, cooling in a furnace, which is very controlled.

So therefore, the same hardness generally we can follow the controlled cooling rate and that actually performs the heat treatment process here, generally creates the very reliable increased ductility and tensile strength and elongation is basically important following the annealing and of course grain size is often very big because annealing process, the cooling rate is very slow. So having sufficient time for grain coarsening effect during this process.

But if you follow the normalizing also in the casting product, then in these cases we bring it up to the recrystalization temperature and then by soaking, then allowing certain time and allow to cool to the atmosphere. But of course the normalizing rate of the cooling is different, relatively more as compared to the annealing process. So in these cases, the grain seemed to be less regular because the cooling rate is different from what we follow in case of the annealing process.

So therefore, normalizing creates smaller grain as compared to the annealing process. So therefore it becomes much stronger or harder where anneal metal, that also can also be predicted in case of the fine grain structure normally produce high strength as compared to the coarse grain structure. So from that sense, if you follow the normalizing treatment of a particular product, we can expect that the strength is more as compared to the annealed product even in a casting component.

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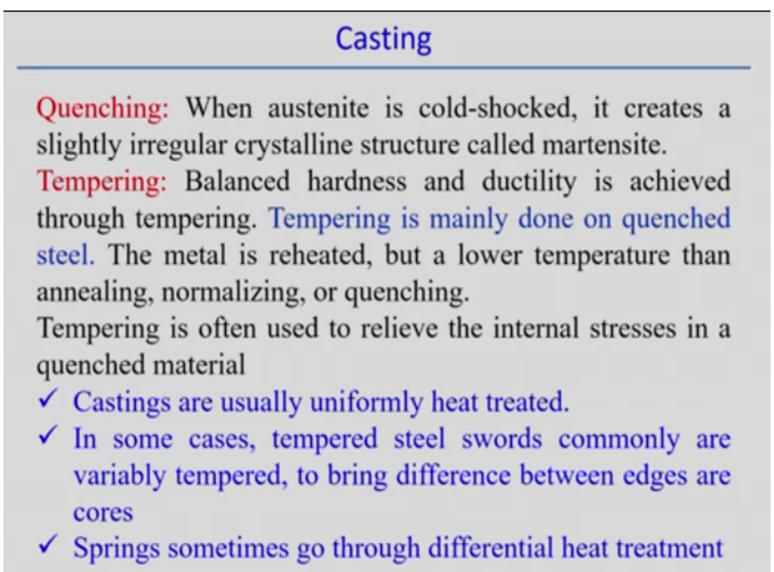

Of course in casting component also, we follow the quenching process and austenite is a cold-shocking that means austenite structure is to follow the quenching process, which is rapidly cooling if we follow austenitic structure, then it creates slightly irregular crystalline structure and that is we know, it is martensitic structure it creates and that quenching can also be followed in certain casting component also.

Then after quenching, normally follow the tempering process, so in these cases, balance hardness and ductility is achieved through the tempering process. So tempering is mainly done when quench steel. Definitely we have already discussed these things. In these cases, the metal is heated, but at a lower temperature than annealing, normalizing or quenching temperature. So therefore, in tempering process we heat the sample to its temperature which is lower as compared to the annealing, normalizing or quenching or other kind of treatment processes.

So tempering often reduces the internal, relieves the internal stresses in a quenched material. So that is why it brings the uniformity in structure, we normally follow the tempering process after quenching. Casting is usually uniformly heat treated in most of the cases, in some cases tempered that not necessary to follow the uniform heat treatment process. For example, the steel swords commonly are the variably tempered the different temperature to bring the difference in the properties the age and the core.

So therefore, in those cases we can follow the different temperature or different cooling rate in case of tempering process to bring the difference in the properties. Sometimes, in case of springs also we can go through the differential heat treatment processes to bring the difference in the properties at the different part of a spring. So that can also be done through the heat treatment process.

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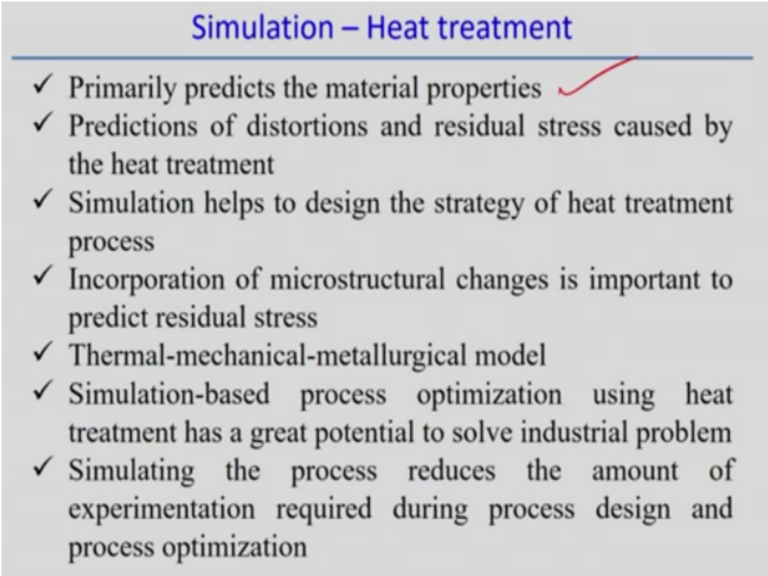

After discussing the heat treatment process, which is relevant to the different kind of the manufacturing processes, now try to look into what we can do the simulation of the heat treatment process, because sometimes the simulation helps to correct heat treatment process particular before not much trial and error method experimental, because most of the cases experiments are very costly to perform the heat treatment process.

Of course time is another method, so therefore, simulation sometimes help, proper simulation can help to get some direction that to design up the heat treatment process particular component, but nowadays several simulation tools are available or softwares are available in the market, but the simulation normally, in simulation tool associated with the heat treatment process normally predicts the material properties that is normally available by following the simulation, that is possible to do the simulation of the heat treatment process.

But of course it is also important in the simulation, but the prediction of distortion of a particular component after heat treatment process what may be the distortion normally happens and what is the residual stress level exists within the structure that is other area, we can perform the simulation process. So in these cases simulation helps to design, if we understand, if we do the prediction of the different material properties of the heat treatment simulation.

Or if we perform, able to predict the distortion of residual stress in that cases, simulation also helps to design the strategy of the heat treatment process. So heat treatment process or design of the heat treatment processes means up to what temperature we can raise the temperature in a particular component and then up to what extent we can keep or we can see soaking of a particular component and then what cooling rate we should follow.

All these kind of information can be output from the simulation of the heat treatment process. So of course, if we look into the incorporation of the microstructural changes during the heat treatment process, that helps to bring the precisely calculate the predicted residual stress and distortion even in case of the simulation of the distortion and residual stress. So in those cases, we need, it is also necessary to form like other processes, like manufacturing processes to develop thermal, mechanical and metallurgical model.

Thermal models means which is associated with heat application of heat. So it is associated with heat treatment process as well. Mechanical means whatever we can estimate the residual stress and distortion in the structure that corresponds to the mechanical model and metallurgical microstructural changes. So combining all these things and interaction between thermal, mechanical and metallurgical model able to predict very precisely the final expected properties of a structure.

That structure is actually the output through the different heat treatment process. So therefore apart from that simulation based process optimization can also be done using the heat treatment, which is having the great potential or normally people are using in order to solve the different kind of the industrial process. So what way we can, if you understand, if you develop the model, you can perform the simulation on this thing.

Then simulation response is optimized, we can optimize the process, shook in the process, maybe such that we can able to predict the structure. Similarly, finally simulating the process actually reduces the amount of the experiment, definitely if you correctly perform the simulation that actually reduces the amount of the experiment as well as time required during the process design and process optimization.

So that kind of benefit from the simulation can also be achieved to avoid extensive experimental effort to get a particular desired product, desired properties of a particular product and that is normally done through the heat treatment process. So thank you very much for your kind attention.