

**Indian Institute of Technology Kanpur**

**National Programme on Technology Enhanced Learning (NPTEL)**

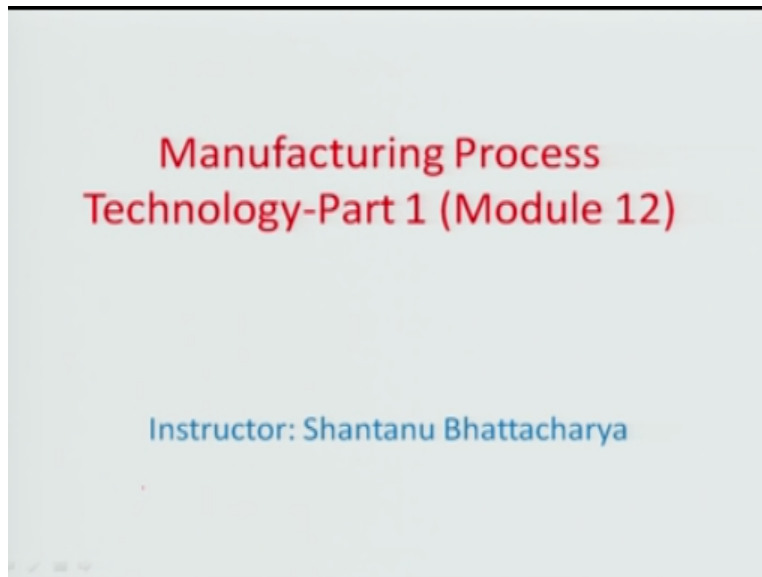
**Course Title  
Manufacturing Process technology – Part- 1**

**Module – 12**

**by  
Prof. Shantanu Bhattacharya**

Hello and welcome to this manufacturing process technology part 1 module 12.

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We were talking last time about equilibrium phase diagram particularly in context of iron- carbon equilibrium diagram and saw the various important transformation like the eutectic, eutectoid, the peritectic transformation which was talking place in context of the change in phase of iron in to two phase or single phase so on so forth.

So we also discussed about the utility or the point at temperature  $723^{\circ}$  C which is concerned with heat treating the material to have different strength or different hardness within the material so it is extremely high engineering relevant and in context of that we are going to discuss today the control of material.

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## Control of material properties

- The material properties of metals and alloys can be controlled by various methods to make the material suitable for a given application.
- These methods include (i) alloying (ii) heat treatment, and (iii) mechanical working and re-crystallization.

**Alloying:**

- Alloy steels are broadly classified into two categories, viz., (i) low alloy steels and (ii) high alloy steels.
- In low alloy steels, the total content of the alloying elements, such as Cr, Ni, Mo, V, and Mn is kept within 5%.
- Each alloy element imparts a specific property to the original material.

Element	Effect	Remarks
Al	Promotes deoxidation Prevents cracking Retards grain growth	Typical low percentage
C	Increases hardenability	Typical percentage 0.25-0.50% Used in steel with carbon content less than 0.25%
Cr	Increases impact strength slightly Contributes to cold hardening Retards hardening during tempering	Typical percentage 0.5-1.0% Used in steel with carbon content less than 0.25%
Mn	Increases hardenability Increases resistance to corrosion, oxidation, and wear Increases high temperature strength	Typical percentage 0.3-0.7% to increase hardenability Typical percentage 0.8-1.0% to increase corrosion and wear
Ni	Increases corrosion resistance	Typical percentage 0.1-0.4%

Properties which are very important you know for metals and even alloys which have to be used for different engineering applications where the requirement of the hardness or the requirement of strengths are varied in nature so the material properties of the metals and alloys can be controlled by various methods to make the material suitable for a given application .

For example one of them is just alloying where your using some trace amount of materials each of which would create some kind of a difference in you know crystal structure by either pre **hardening** it or doing something related to the regularity of the **lattice** structure of the **metal** where enhanced properties can be felt coming out. heat treatment where you can rapidly heat and cool.

And this can also result in quite a bit of changes in the structure the crystal structure of the material which can lead to you know the various changes in the material properties and the obviously the mechanical working and re-**crystallization** which is another way in which strain **hardening** can be induced and then the temperature can be taken just to above you know the re-**crystallization** temperature.

So that it can start a fresh and be able to hard to an extent that it want it to be harden. so think of it and then the manufacturing process when we are talking about a primary or secondary process and we want a **desired** property like for example **desired** ultimately strength or desired hardness on the surface of a material. you will not only need to worry about the primary or secondary

manufacturing process but also the after effect of putting the material coming out of these process is into use you know use engineering use.

So for example in assembly of different linkages when each of this link as been formulated through a manufacturing process if enough amount of surface **hardness** enough amount of surface stability is not there or in fact if there is low ultimate **yield** strength of the material then linkage may completely fail okay. so then that is the reason why these **heat treatment** process is become very, very important from the aspect of manufacture. so the first process alloying.

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**Control of material properties**

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**Alloying:** ✓

- Alloy steels are broadly classified into two categories, viz., (i) low alloy steels and (ii) high alloy steels.
- In low alloy steels, the total content of the alloying elements, such as Cr, Ni, Mo, V, and Mn is kept within 5%.
- Each alloy element imparts a specific property to the original material.

Element	Effect	Remarks
Al	Promotes deoxidation Promotes nitriding Restricts grain growth	Typically low percentage
B	Increases hardenability	Typical percentage 0.001-0.003% Used in steel with carbon content less than 0.6%
Cr	Increases tensile strength slightly Contributes to red hardness Retards oxidation during tempering	Typical percentage 0.5-2% to increase hardenability Typical percentage 0.8-1.0% to increase corrosion and wear resistance
Mn	Increases hardenability Increases resistance to corrosion, oxidation, and wear Increases high temperature strength	Typical percentage 0.1-0.2%
Ni	Increases corrosion resistance	Typical percentage 0.1-0.4%

Obviously concerns the way that alloying of steels happen mostly. so **let say** in the alloy steels they have got be classified into two categories, **one** is called a low alloy steel and another is a high alloy steels. so in the low alloy steels the total content of the alloying elements such as chromium Ni, Mo, and V and **Mn is kept** within 5% and each alloy element **imparts** of specific to the origin material. **I am just try to assemble some of** the properties which would be induced while this different like aluminum.

Tries to promote **deoxidation, promotes de-nitriding restricts grain growth typically a low percentage is something which is desirable. the material Boron** for example increases harden ability typical percentage 0.001 to 0.003% and using steel with carbon content less than 0.6% often, which gives the effect of incase hardenability. you have Cobalt which can impair impact

strengths impair the impact strength slightly, it contributes to the red **hardness**, or sustains hardness **during** tempering.

You know you have chromium which increases **hardenability** again increases resistance to corrosion, abrasion in where increases temperature strength and typical percentage is which we need of these chromium material is between 0.5 to 2 to increase hardenability and 4 to 8 to **increase the corrosion and wear resistance**, so it is very important material from corrosion aspect okay. then the material copper which can increase corrosion resistant again typically the percentage that is linear it is 0.1 to 0.4% so these are some of the materials which can actually **impart** desirable Properties are effects by alloying into the basic crystal structure of iron. so you have a variety of other in the key in the same manner.

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**Control of material properties**

Table 1.3 Effects of alloying elements on steel (cont.)

Element	Effect(s)	Remarks
	Counteracts brittleness from S	Typical percentage 0.25-0.40 to counteract brittleness from S
Mn	Increase hardenability Increases resistance Reduces ductility and weldability Increases hardenability significantly	Typical percentage > 0 to increase hardenability
Mo	Increase strength, toughness, red hardness, and hot strength when used with Cr, Mn, and V Enhances corrosion and abrasion resistance	Typical percentage 0.2-5 Used for HSS cutting tools, forged crankshafts, turbine rotors, high pressure cylinders and boiler plates, and gears
Ni	Increase toughness and impact strength Improves corrosion resistance	Typical percentage 2-5 to increase toughness and strength Typical percentage 12-20 to increase corrosion resistance Used in cast hardened parts such as high speed gears and bearings
P	Increase hardenability Improves machinability Increases strength in low carbon steel Improves corrosion resistance	

For example what Mn does is to sort of contract the **brittleness** from the sulphur which otherwise gets generated into the mold, because the sulphur is something that you have to get **rid of** because if otherwise it generates a lot of you know undesirable properties related to **brittleness** etc the **casting**. so typical percentage is about 0.25 to 0.40% to contract the brittleness from

sulphur. Similarly manganese can increase hardenability, increase resistance, reduce ductility and weldability. Increase hardenability significantly, percentage again greater than 1 to increase the harden ability.

Molybdenum in them for example increases strength, toughness, red hardness and hot strength when used with chromium, manganese and vanadium I mean total. so typical percentage here that looking at a 0.2 to 5%. in fact Molybdenum is used a lot in high speed cutting tools a particularly high speed steels you know it is used in forged crankshafts, turbines, rotors, high pressure cylinders and boiler plates, gears so on so forth.

Similarly nickel would increase toughness and impact strength, improve the corrosion resistance. these are some of the typical percent in range this 2 to 5% will increase the toughness strength, 12 to 20% will increase the corrosion resistance and mostly nickel would be used in the case of you know harden parts such as let us say high speed gears, ball bearings so on so forth.

Then the phosphorous, which is again used for increase hardenability, machinability increasing strength in low carbon steels and improving the corrosion overall corrosion resistance. so that is another aspect of the material phosphorus okay, so these are the various effects of alloying.

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**Control of material properties**

Table 1.3 Effects of alloying elements on steel (cont.)

Element	Effect(s)	Remark(s)
	Strengthens low alloy steels	Typical percentage 0.2-0.9 to increase strength
	Increases hardenability	Typical percentage 2 Used in spring steels
Si	Acts as deoxidizer	
	Improves magnetic properties when present in large percentage	Typically high percentage to improve magnetic properties
S	Improves machinability of very low carbon steels	Typical percentage 0.05-0.15 Normally considered as impurity
Ti	Increases austenitic hardenability	
	Reduces martensitic hardness in Cr steels	Fixes carbon in inert particles, resulting in remarkable carbide forming effect
	Increases strength while retaining ductility	Typical percentage 0.1-1
V	Produces fine grain size	Forms stable carbides that persist at quite high temperature
	Increases hardenability	Normally used in combination with chromium
W	Imparts hardness and wear resistance	Typical percentage 4 to impart wear resistance
	Significantly improves red hardness	Typical percentage 18 to improve red hardness
	Imparts strength at high temperature	
		Used in high speed tool materials

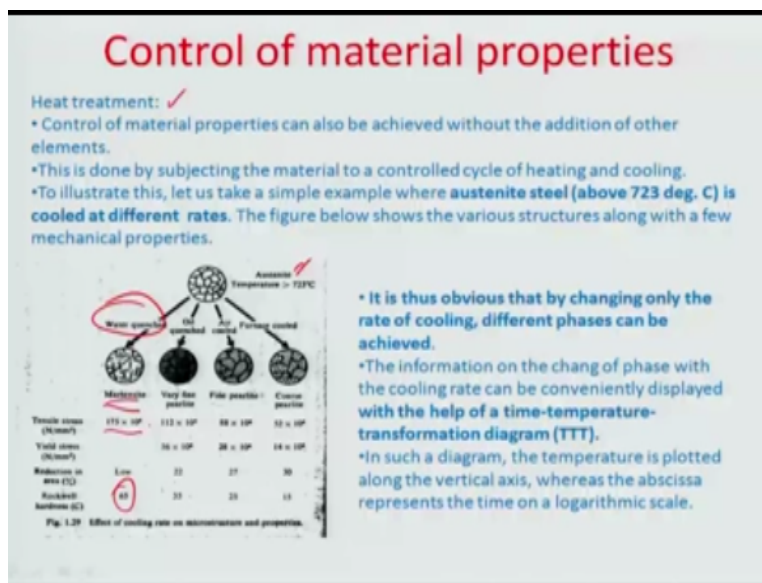
You know the elements on steel similarly you can say silicon acts as a deoxidizer or improves I mean magnetic properties are present in large percentages or sulphur which improves machine

ability of low carbon steel but it creates a lot of brittleness within the structure which is one of the reasons you want to get rid of the sulphur mostly in castings etc.

Titanium, which increases the **austenitic hardenability** and reduces the **martensitic hardness** in chromium steels. Again **Vanadium**, which increases strength while **retaining ductility**, produces fine grain size, increase **hardenability** and tungsten, which imparts again hardness and **wear resistance**, significantly improves red hardness and **imparts** strength and high temperature so these are some of the consolidated effects of alloying steels by the various trace elements.

In the first stage that you are seeing here are mostly very trace concentrations until something like you know and it is quite remarkably low sometimes in comparison to even the primary material which is alloying which is that of carbon actually.

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So the other process which is important for me to discuss is heat treatment, so not only alloying but supposing there is a pure **phase** unless an alloy **phase** material which is there let us say, steel is a alloy of carbon and iron right. So how can we achieve the properties of steel material properties of steel by not adding any **other** alloying element but on the trying to see the diffusion driven transport of the carbon with respect to the overall crystal structure of iron gets at certain rate you know equilibrated rate and so that gives you and a sense of what is going to be the overall hardness etc, of the structure.

For example, let us say if I had **Austenite** and if I wanted to heat it very rapidly by water quenching it and cold water, immediately you will get **martensitic** state which is known for its hardness in fact on the **Rockwell** hardness scale it reads about 65 you know and then it has more tensile strength like  $175 \times 10^4$  N/mm<sup>2</sup> and it also reduces in area percentage of the **reduction** is very low okay.

Similarly if you want to **oil quench austenite**. for example you not very fine **pearlite** which also **would** have 35 **hardness** and it would have a ultimate yields stress you know of about  $56 \times 10^4$  and **tensile strength** as of  $112 \times 10^4$  okay. or if I and if you could just heated by air cooling just directly you know just **keeping** in to normal room temperature after the heat to be in process.

So that results in fine **pearlite** now why is this difference structures are produced is because you now giving it enough equilibrating time in one case when you are rapidly cooling it visible is the case when you are slowly cooling it, so the equilibrating time for the diffusion and the mechanically driven diffusion process of carbon and to the matrix happens and the **different** rates okay or in to the different cooling rates.

So here for example it is a **Furnace** cooled case, we are **austenite** converts in to the **pearlite**. this is the **slowest cooling** process okay. so you already keeping it in the **Furnace** and **allowing** the material to cool in the **Furnace**, so that is the slowest cooling that you can say for that produce a difference structure all together, course **pearlite** which has a very low **Rockwell** hardness of about 50 you know.

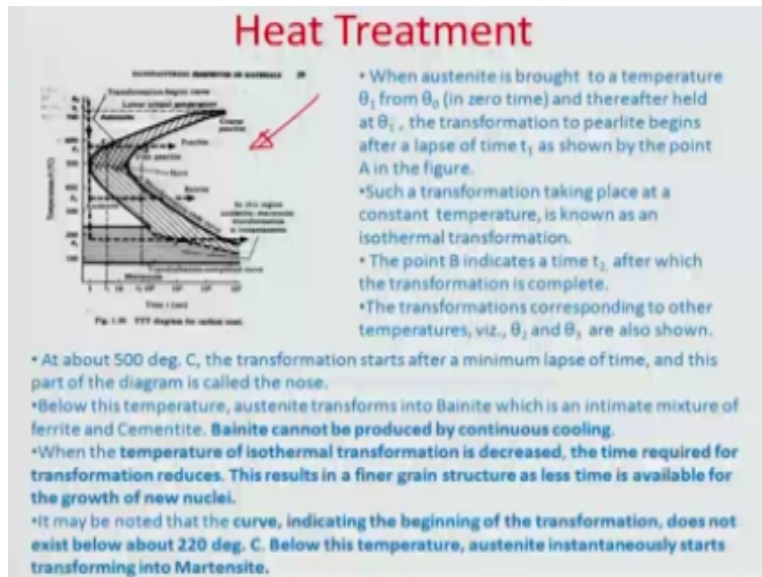
So as supposed to **martensitic** which was with rapid cooling you can see these are immediately coming through where very low hardness is **recorded only in changing** a cooling rate okay. So that is why as I was earlier discussing this 723<sup>o</sup> C temperature is very important because beyond this, the **Austenite** steel is completely  $\gamma$  iron and then you know we just changes from that  $\gamma$  and various states corresponding to the different cooling rates that are used you know at that particular point.

So it is does obvious that by changing on the rate of cooling different phases can be achieved and so in order to **address** this issue the cooling rates have to be demarcated in one page **format**, just like you saw the phase diagram included the phase diagram and so these curves are known as the time temperature transformation curves or TTT curves and I am going to illustrate you how this



TTT curve can be read and what actually is inter predict out of it so let us say the temperature is plotted you know in the vertical axes where the whereas the abscissa represents the time on a logarithm scale.

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So normally this write about here is what the TTT curves look like. Let me just know it to little bit more you know then let us say magnify the curve little more.

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So here for example as you can see the transformation. it begins from this particular temperature which is probably 723<sup>0</sup> C and you know when let us say this is where austenite stage is present we called it as austenite here okay so it is  $\gamma$  iron you can say with the FCC kind of you know



structure ferrite is represent all through the  $\gamma$  iron phase okay we start at  $\theta_0 = 723^\circ$  and let us say if we try to cool the iron at certain rate which is given by this slope right about here.

This is time scale and this is temperature so basically when I am saying this slope of this particular line as I am showing here it is actually the cooling rate is that we are referring to you know so the logarithm of cooling rate that we are referring to so when **austenite** is brought to a temperature let us say  $\theta_1$  from  $\theta_0$  had extremely high cooling rate which can be considered almost equal to let us say 0 time.

You know because the rate is very, very high so you are changing from  $723^\circ$  let us say  $\theta_1$  this is just below  $600^\circ$  Celsius at this point we are leaving and then allowing the transformation process to take place the transformation to **pearlite** as you can see here begins after some point of time you know so this much time let us say this is  $t_1$  this is **spent** in **waiting** so that there is a mechanical diffusion which works out.

And this phase right here which start after this solid line here is the **coarse pearlite** phase you know so this is the **pearlite** transformation happens to take place at start to take place from temperature  $t_1$  okay. so you have to really at start to take place from temperature  $t_1$  okay so you have to really wait by dropping down to  $\theta_1$  in almost no matter of time.

And then wait for this  $t_1$  time for this the transformation to start taking place from **pearlite** you know so once this is done this **pearlite** transformation sort of completes up to the point B here let us say this is time  $t_2$  so the curve here for example in this particular zone actually represents the end of production of complete **pearlite** the region here is completely you know full of **pearlite** you have **coarse pearlite** or fine **pearlite** towards the curve here or at the border you have.

You know this is sort of **Bainite** transformation so here for example in this particular case coming from  $t_1$  to  $t_2$  that means from point A to point B you know we can call this transformation is an **isothermal** transformation and one of the reasons why that is told that you know doing this transformation all temperature  $\theta_1$  without change.

So the transformation corresponding to the other temperature  $\theta_2$  and  $\theta_3$  for example if this know allows to cool off **beyond**  $\theta_1$  or all shown here for example if you directly goes into rapid cooling mode where the time **spent** in cooling is very low and you can see that, so it enters this into the **martensitic** phase. So whatever I was showing there diagrammatically in terms of

structures and cooling this has been represented in this TTT one snap shot now we can change the rate of cooling and attain any structure that you would like for the material to come up with.

About 500° C, the transformation starts as you can see after minimum laps of time, so this area is therefore know as the nose of the curve TTT curve and it is sort of you can see that the cooling rate is almost **tangential**, if the cooling rate anywhere lower to the rate that the extremely high arte that as shown here. **Then there would be production of pearlite phase which would come up here ok.** Because then rate will start and go through this whole **pearlite** region before getting into state.

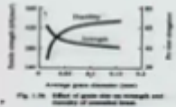
But if you are having a rapid pointing like this almost **zero** time then just go tendency with the nose and avoid getting into the **pearlite** zone and go into the **martensitic** zone. So below the 500°c temperature the austenite suppose if I drop it somewhere here at  $\theta_2$  it would now isothermally convert into **bainite**. it will not give you **pearlite** anymore okay. So beyond this particular and it will not be able to get into the **bainite** unless it crosses over the **pearlite** zone which is here.

As a function of time so ultimately you get the **bainite** but it comes true this zone wise right here okay, so that is how you interpret from the time temperature transformation curve in the various structures, based on different you know time points. The other issue that I would like to discuss is only about the mechanical working and re crystallization.

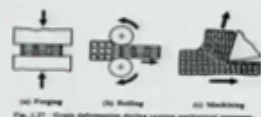
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**Mechanical Working and Recrystallization**

- As already mentioned, the mechanical properties, e.g., strength and hardness, of a polycrystalline material are also governed by the grain size of the material.
- The figure below shows the nature of variation of two mechanical properties with the average grain size.



\* The grain size can be controlled by mechanical working and recrystallization. As we have already noted, the effective size of a grain is decided by the volume to surface area ratio.



\* The figure on the right shows how the grains are deformed by various mechanical working processes. Here we can easily see that the effective grain size is reduced because the surface area of each grain increases, whereas the volume remains the same.

- It is possible to restore the original grain geometry by heating the material up to a temperature where the new fine grains are formed.
- The process is called recrystallization and the temperature needed to achieve this is known as the recrystallization temperature.
- If the material is kept for a considerable period of time at this temperature, the newly formed fine grains grow in size.
- On the other hand if the material is cooled quickly, the grain size remains small. It should be noted that in the mechanical working processes, the grains are deformed, whereas in recrystallization, new grains are formed and their size can be controlled.

And as I mentioned here the mechanical properties example strength and hardness of the polycrystalline material are governed by grain size of the material. You have earlier looked into the dislocation theory where we assume that if there is the **jamming** of the dislocation **across the grain boundaries** while travelling there is going to be an **increase in strain hardness**. **Strain hardening process would try to take place so that overall hardness is changed because of that.** So here the strength and the hardness of the polycrystalline material are really a function of the grain size.

So meaning there if I wanted to do mechanical working on the material for example. Let us say we have shown three cases here and mechanical working is **being** done. this is then case of **forging** so circular grains otherwise are converted into **elliptical** here. in case of rolling where there is circular **grain being converted** into **elliptical** as you can see by a **roll pressure or machining where the circular grain again are been converted into a elliptical by means of the tools etc.**

So here during the grain deformation processes, there are going to be various you know **mechanically structured grains going to be formulated** and obviously the grain structure changes because of **the deformation that is going to be change in the overall ductility or strength properties of the material.** So you can look at it the tensile strength if you can plot as a function of **grain diameter**, the increase in the **grain diameter** that ductility will increase and strength **would reduce ok.** So the other aspect **here** is that mechanical working can be followed by a recrystallization where there is again fresh **grain** growth.

Because you are now **taking it above 723 degree Celsius to the gamma austenitic phase and bringing it down okay.** so even that recrystallization process can be initiated with mechanical working **so that you** can have a control on the overall grain size which would determine your ductility and strength properties. So in **nutshell** then we have looked into the various aspects for how you alloy the material to control the strength. we have also looked to control the strength we have also looked into various aspects of how you heat treat to control these strength and then able to read from the single snapshot how the strength is going to change or how the structure is going to change based on different rates of cooling okay.

And finally you have also looked into mechanical working and **recrystallization** processes. so the figure on the right show the grains are deformed by various mechanical working processes. you

can easily see that their effective grain size is reduced because the surface area of the grain increases where the volume remains the same. it is possible to restore the original grain geometry by heating the material up to temperature where the new fine grains are formulated and that process is known as the recrystallization.

And compute and leave it to achieve this is known as the recrystallization temperature and the material is kept for a constitution period of time at this temperature the newly formed fine grains will grow in size and again formulate this similar original property of the material. on the other hand of material is cooled quickly the grains size are small and it should be noted that in mechanical working process the grains are deformed where as in recrystallization new grains are formed and their sizes can be controlled.

So you can play around with the way that you cool after the crystallization and even before recrystallization do mechanical working to reduce the grain size to a desirable level okay. that way we determine the mechanical properties with that I would like to close on this module in the next module we will start understanding the casting process in great detail so I think we have now enough understanding about material properties for us be able to go into the modeling and design of casting so with that I would like to close this module thank you.

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