Powder Metallurgy

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Lecture - 35
Powder compaction - 2

Hello and welcome back. So, right now, we are talking about the compaction process and in the previous class we discussed about the compaction mechanism.

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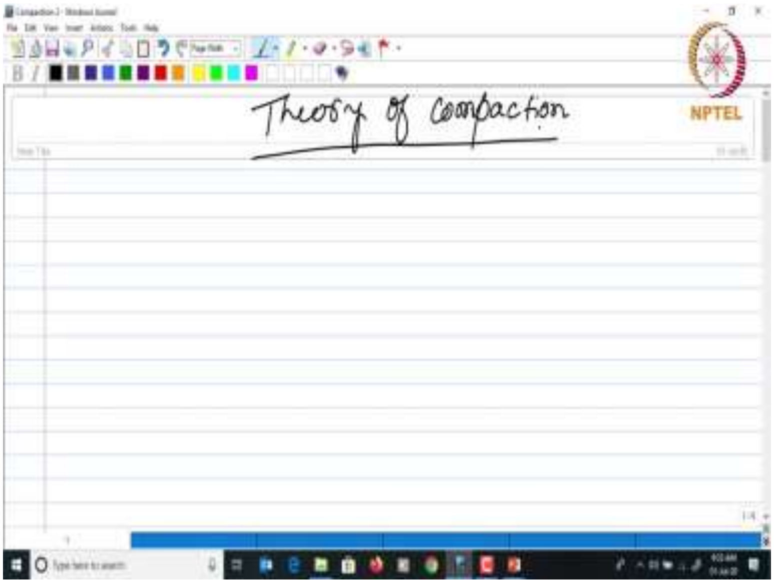

In this class we are going to continue on this and learn about the compaction theory with regard to the pressurisation. So, in this class we are going to discuss about the theory of compaction. Compaction is all about pressing a loose mass of powder in order to provide a shape to it. So, in the compaction theory, we are going to look at how the pressure is going to be distributed inside the die as the powder is being pressed.

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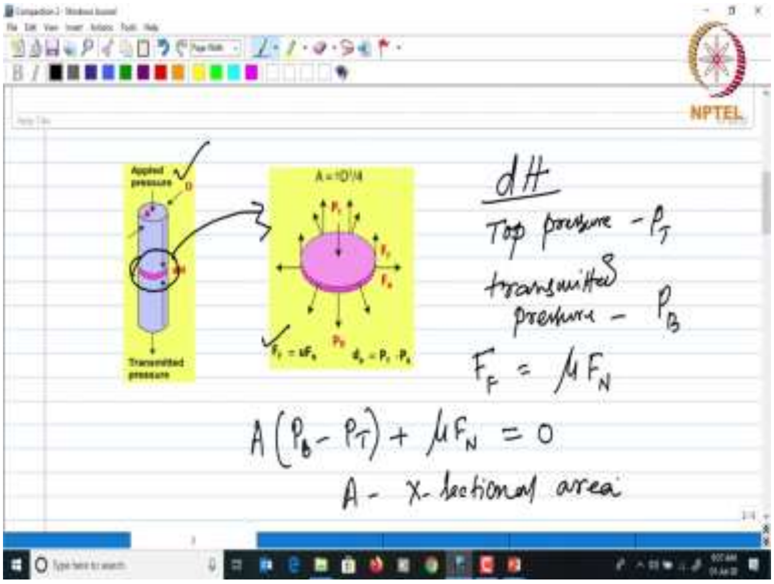

So, let us consider a cylindrical compact of diameter D and height H which is over here. So, this compact is pressurized. So, let us consider a thin section dH from this compact and see how the pressure is distributed. So, if you look at the forces acting on this thin section dH, the pressure at the top is P_T and the pressure which is transmitted through the bottom is P_B.

The pressure which is applied at the top and the transmitted pressure will differ due to the friction between the powder particles and the diode. So, there is a friction force here as you could see this is the friction force $F_F = \mu F_N$,

where μ is the friction coefficient and F_N is the normal force. So, if you take the balance of forces on this section dH.

Then this is what you will get,

$$A(P_B - P_T) + \mu F_N = 0$$

where A is the cross sectional area. Now, this normal force F_N depends on the applied pressure.

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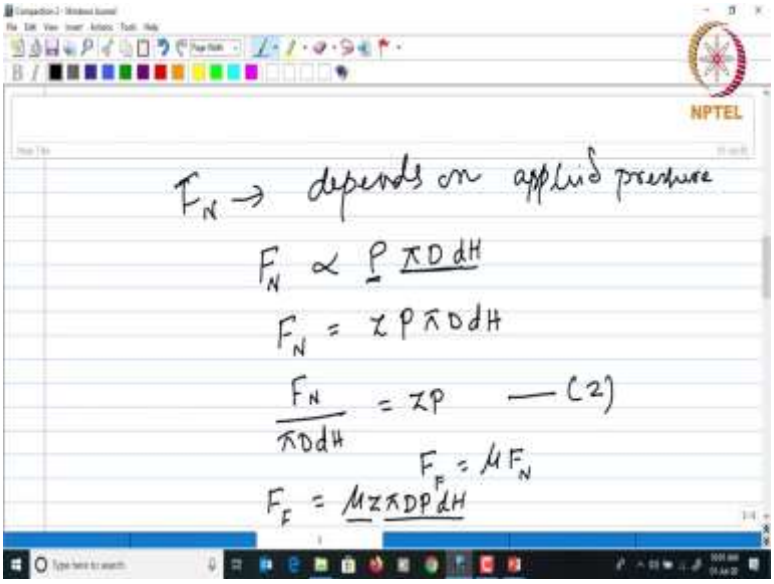

And hence a proportionality constant that depends on the compact density can give a ratio of the radial to the axial stress. The radial stress of course, is the normal force as you could see from here and the axial force is the pressure multiplied by the area on which it is acting.

And therefore, you can write that F_N is proportional to P which is pressure multiplied by the area on which it is acting and that is

$$F_N \propto P \pi D \, dH$$

So, this is the area on which the pressure P is acting and as I said F_N is proportional to this force and we can introduce the proportionality constant, let us call that z and by rearranging we can write, we can write it in the form of equation 2

$$F_N / \pi D \, dH = ZP \quad \ldots\ldots 2$$

and the frictional force is μ F_N as we know and if we substitute F_N over here, we get the frictional force as this one.

$$F_F = \mu z \pi DP \, dH$$

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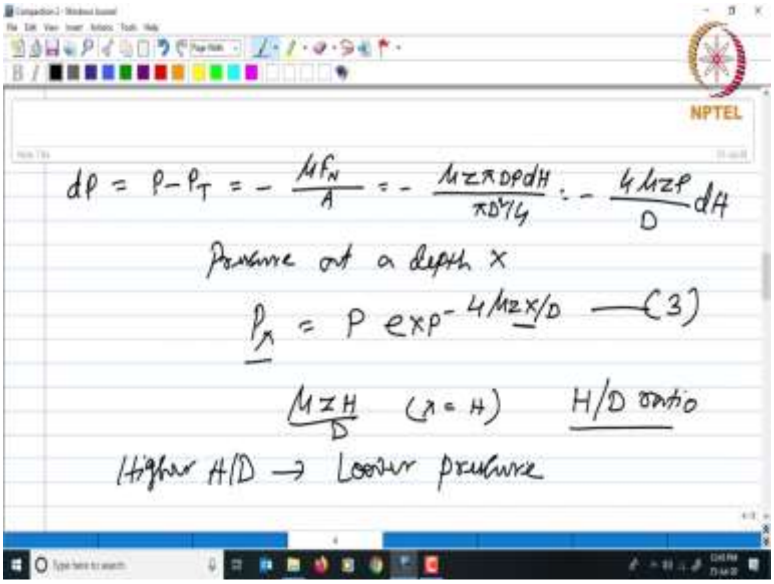

Now, the pressure difference dP is $P - P_T$,

where P is the pressure at a particular depth in the compact and P_T is the pressure at top, this is equal to

$$P - P_T = -\mu F_N / A = -\mu z \pi DP\, dH / (\pi D^2/4) = -4\mu z P dH / D$$

which will again come from the balance of forces and if we integrate this, then we can get the pressure at the particular depth X

$$P_X = Pe^{-4\mu zx/D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

So, you can see from here the pressure depends on the depth at which we are measuring it and also this particular parameter $\mu zH / D$. So, basically it tells you that, it will depend on the height by diameter ratio or the H / D ratio. The pressure would depend on that or the distribution of pressure would depend on the H / D ratio.

So, if you look at this equation 3, you would see that for higher H / D ratio, the pressure will be lower. Higher the H / D ratio, lower will be the pressure and on the other hand high pressures will result in shorter compacts with large diameter.

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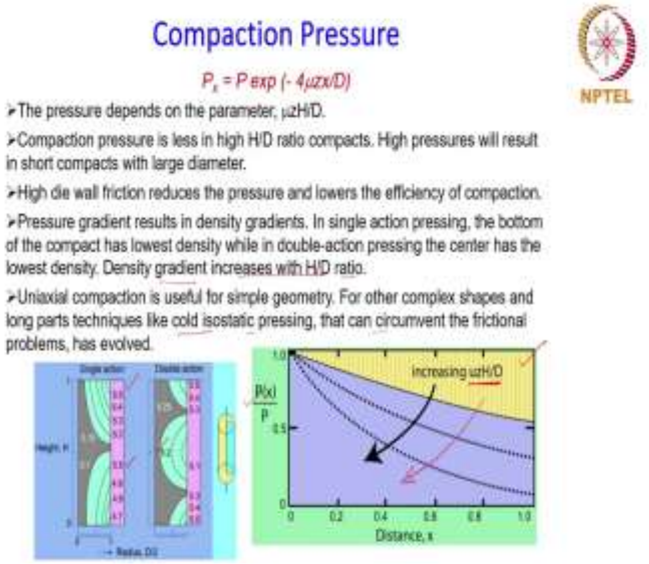

High die wall friction will reduce the pressure and it will lower the efficiency of the compaction and that is why it is necessary to lubricate the powder and also the die wall in order to reduce the friction and because of this difference that you see in the pressure at different depths in the compact, there is the pressure gradient from the top to the bottom of the compact.

And the pressure gradient is not desirable because the pressure gradient will give rise to a gradient in the density also and therefore, the green density which is obtained in the compact will not be uniform throughout the compact. So, if you look at the density gradients for uniaxial pressing, this is how it looks like for the single action and the double action pressing.

So, we are considering a compact with same height, but in one case it is pressed by single action, that is the pressure is applied by one punch and in the other case it is double action, where the pressure is applied by both the punches,. So, now, you can see how the pressure varies across this, if you see at different depth or different height into the compact.

This is how the pressure varies or the pressure gradient is for the single action at the top and at the middle you have high pressure and the bottom has the lowest pressure in case of single action pressing, while in case of the double action pressing, the centre has the lowest pressure and as a result it will have the lowest density also.

So, as I was mentioning, this pressure gradient is not desirable because it will give rise to density gradient and if the green density is not uniform across the compact, it is going to lead to some problem during the sintering process, because during sintering all the pores will close and as a result of that, the compact will shrink and the shrinkage depends on the green density lower is the green density, higher will be the shrinkage.

And if the green density across the compact is not uniform, the shrinkage will also not be uniform and as a result of that, it will be difficult to maintain the dimensional tolerance in the compact, when it is being sintered and the final product is met. Since, the shrinkage will be different at different places. The dimensions will also differ from place to place, ok.

So, this is why density gradients or the pressure gradients are not desirable in a compact and our objective should be to make it as uniform as possible and right over here you can see a plot which again depicts the effect of this parameter $\mu zH / D$.

So, as you could see, with the increasing $\mu zH / D$, the effective pressure at a particular depth decreases and therefore, the density gradient will also increase with increasing H/D ratio, when the H /D ratio exceeds 5, die compaction will becomes unsuccessful. A low compact height on the other hand allows for successful single action pressing; however, double action pressing is predominant because the application of pressure in double action is more effective compared to the single action process.

So, for all these reasons uniaxial compaction is useful for simple geometry, but for other complex shapes and long parts techniques like cold isostatic pressing, that can overcome the frictional problems will be more suitable. So, this is all about the different aspects which control the densification during the uniaxial pressing operation. So, let us look at the green density now, because it is a very important parameter as we have seen by now.

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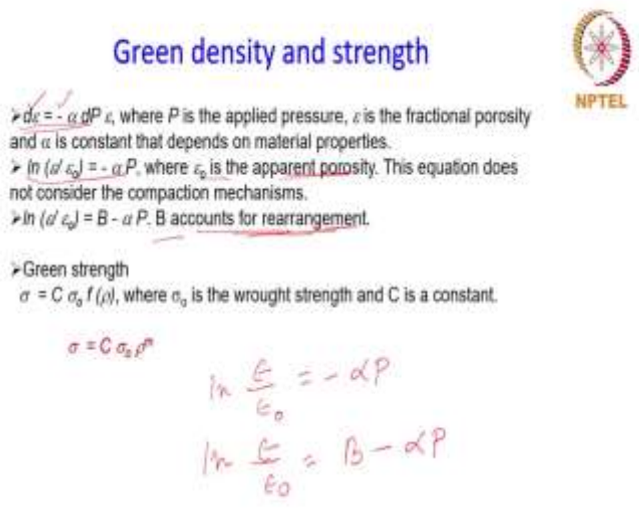

So, green density or the fractional porosity which remains after the compaction process is the function of the applied pressure, that you can see from here, from this particular relationship,

$$d\varepsilon = -\alpha dP\,\varepsilon$$

where epsilon is the fractional porosity; P is the applied pressure and alpha is a constant which depends on the material properties and the negative sign that you have here that indicates a decrease in the porosity or densification.

So, as you applied more and more pressure, you expect the porosity to decrease and the compact to densify. So, if you integrate this equation you would get this,

$$\ln \varepsilon / \varepsilon_o = -\alpha P$$

where ε_o is the apparent porosity; that means, the porosity at the beginning of the compaction process; however, this equation does not really consider the compaction mechanism, that we talked about before.

So, if you include the rearrangement process, that happens in the beginning before the actual compaction or the closure of pores starts, then this equation can be modified to this one,

$$\ln \varepsilon / \varepsilon_o = B - \alpha P$$

where B accounts for the rearrangement.

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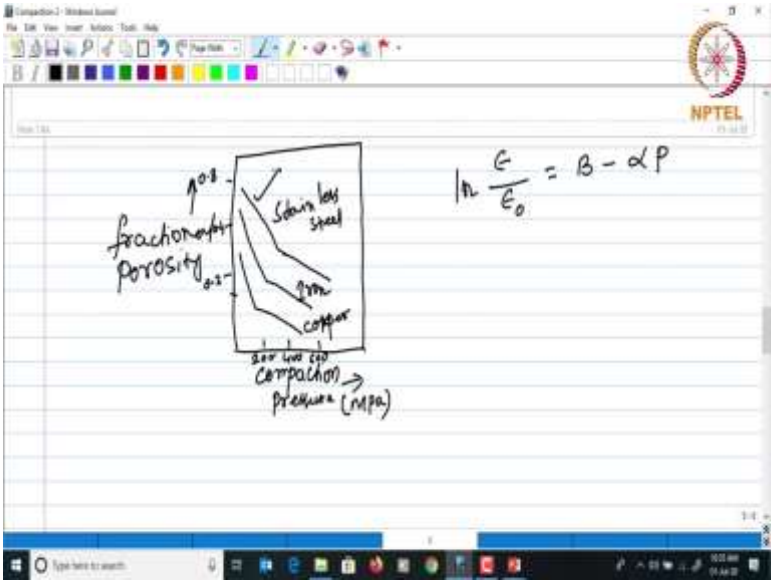

So, if you look at the fractional porosity as the function of the compaction pressure. And the pressure is in mega Pascal. So, as the pressure increases the fractional porosity would decrease something like this and this will be different for different materials. For example, the top one is for stainless steel whereas, the lower most is for copper.

So, you can see at a particular pressure it is around 300 or so, there is a change in the slope and that indicates a change in the compaction mechanism or the compaction behaviour when the pressure exceeds a particular value.

So, the mechanism basically changes from yielding to work hardening as the pressure is increased. So, it also shows that work hardening is the major concern during the compaction process. So, this plot that you see here it basically follows that equation which we derived just now, the equation that correlates the fractional porosity to the compaction pressure. So, as I said you can see two distinct slopes here, one at the lower pressure and the other at the higher pressure.

So, when the pressure is lower approximately below 300 mega Pascal, the behaviour of the material during the compaction process is basically dominated by the yield strength of the material and as the pressure is increased at high compaction pressure, the compaction efficiency decreases because the full density is approached and there are only few pores remaining to be closed and therefore, you know the increase in the density is not that significant as the pressure is increased.

So, therefore, at higher pressure the compaction is primarily dominated by the work hardening behaviour of the material, which you can see in terms of a change in the slope of this line.

And you can also see that copper, which is the lowest strength metal in this series out of the three materials that you see over here. It shows the lowest porosity at all compaction pressure because as I said you know it is the lowest strength material and therefore, it is easier to compact, compared to a material like stainless steel which is much stronger than copper, the middle one is for iron.

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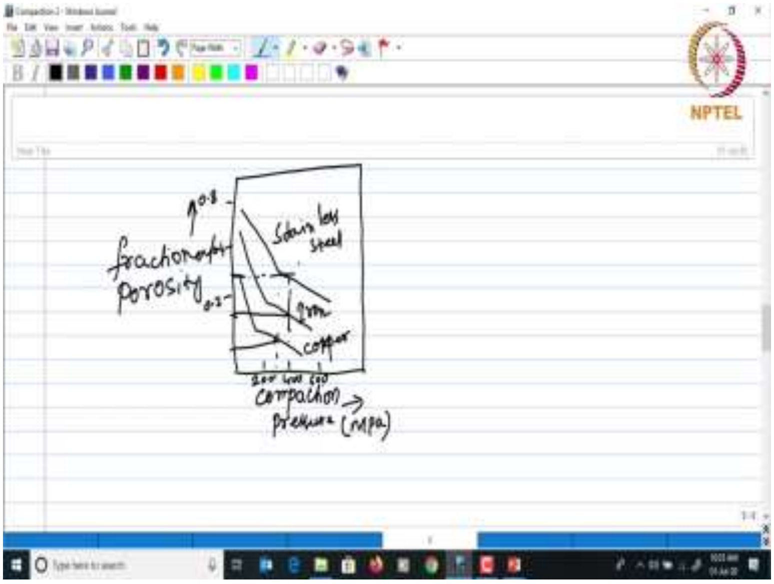

Stainless steel on the other hand is a higher strength material and goes through a rapid work hardening during the deformation process that happens during the compaction and therefore, it exhibits the highest porosity at any given pressure compared to the other two materials, which are of lower strength. So, that is what you can see here, if you take any given pressure let us say this one, the fractional porosity for stainless steel is always higher compared to iron or copper.

So, that is because of the higher strength of stainless steel. So, this is how you can see the correlation between the material property and the compaction process in terms of the green density or the fractional porosity of the compact.

$$\sigma = C\,\sigma_o f(\rho)$$

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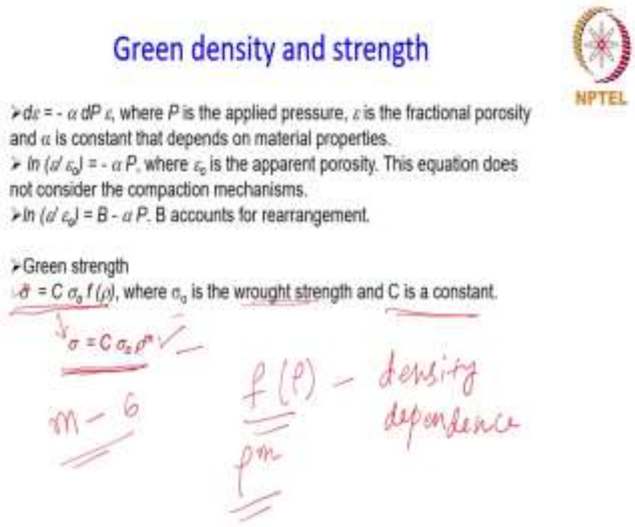

Now, the compact which is obtained after the pressing operation is known as the green compact and it is basically characterised by its density and the strength, which are known as green density and green strength respectively and if you look at the green strength, it will be lower than the material when it is 100 percent dense, because the green compact will have certain amount of porosity.

So, this porosity will first of all lower the effective cross sectional area and the pores also act as stress concentration sites and they are also potential sites for crack initiation and as a result of all these, the green strength will be lower than the material strength or the wrought strength of the material, when it is 100 percent dense. So, if you look at the relationship between the green strength sigma with the compaction process that is given by this particular equation.

$$\sigma = C\,\sigma_o f(\rho)$$

So, it is expected to vary with the fractional density as I just now told you. So, here σ_o is the wrought strength or the strength of the material, when it is 100 percent dense. So, that is the strength of a processed wrought material and C is a constant, $f(\rho)$ is a function of the density or the density dependence.

There are certain forms of $f(\rho)$, but commonly accepted form is of the type ρ^m and therefore, this equation will reduce to this form, in the form of a power law equation like this

$$\sigma = C\,\sigma_o(\rho)^m$$

where the exponent m might have a value of about 6. So, before we finish this lecture, let us take a moment to summarize it.

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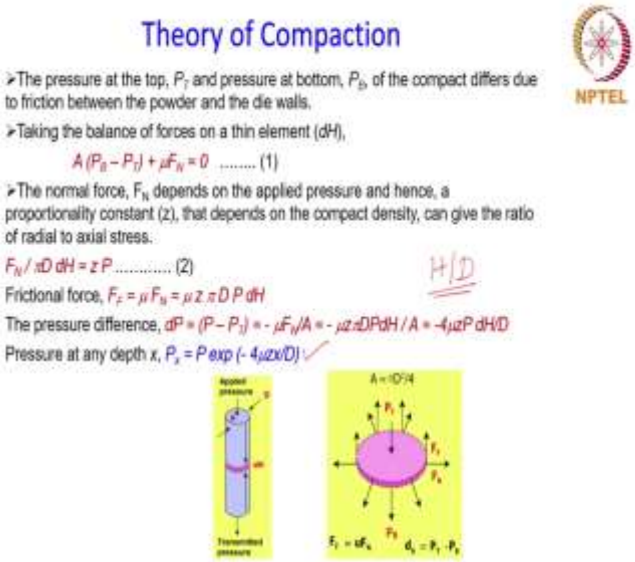

Today we talked about this theory of compaction, to see how the pressure is distributed in the compact, when it is being pressed. So, here we have seen that the pressure depends on the H/D ratio or the height to diameter ratio of the compact and from this equation,

$$P_X = Pe^{-4\mu z x / D}$$

that you have over here you can see as the H / D ratio increases, the effective pressure at a particular depth decreases and because of this dependence which primarily arises due to the friction between the powder particles and the die wall.

There is a gradient in the pressure across the compact, which gives rise to a gradient in the density as well. So, this is the pressure map, that you could see or the pressure gradient in a compact for a single action pressing and a double action pressing compaction process. This kind of gradient in the pressure is not desirable because it leads to gradient in the density of the compact, which will affect the sintering process, specially the shrinkage and the associated dimensional tolerance of the compact, when it is being sintered.

So, therefore, the objective should be to reduce this gradient and make it as uniform as possible and in order to do that techniques like cold isostatic pressing can be used because such techniques can overcome the frictional related problems and therefore, you can expect a more uniform pressure distribution, which will lead to a more uniform density as well. Then we talked about this dependence of the fractional porosity with the compaction pressure.

So, if you plot this dependence of the fractional porosity with the compaction pressure, it gives rise to a straight line, that basically describes the compaction behaviour of a particular material and we have seen that for a high strength material it becomes difficult to compact because of strain hardening that occurs during the compaction process particularly at high pressure and that can be also seen in this plot between the fractional porosity and the compaction pressure in terms of a slope change at higher pressure.

So, that indicates that the compaction behaviour or the compaction mechanism has changed from that of yielding to a strain hardening controlled compaction mechanism. So, if the material has higher strength you can expect higher strain hardening to occur and therefore, at the particular pressure, if you look at the fractional porosity, that will be lower for a high strength material compared to a low strength material.

So, today we have seen a comparison between copper and stainless steel in that particular plot between the fractional porosity and the compaction pressure and we have seen how a higher strength material like stainless steel behaves compared to a lower strength material like copper.

And then finally, we talked about this green strength, that is the strength of the green compact which is obtained at the end of the compaction process and we have seen that it basically depends on the fractional density which is obtained in the compact at the end of the pressing process by an equation like this.

So, you can see that as the fractional density increases, the green strength will also increase because increasing the fractional density means closer of the pores. So, if you have less number of pores you can expect the strength to increase because porosity is one of the main reasons behind a lower strength in the green compact compared to a wrought product which is 100 percent dense and with that we come to the end of this lecture.

Thank you for your attention.