Rheology and Processing of Paints, Plastic and Elastomer based Composites

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Lecture 41
Plastic and fiber-related processing

Welcome to NPTEL online certification courses on Rheology and Processing of Paints, Plastic, Elastomer based composites. Today we are on week 7 lecture number 7.5 titled plastic and fibre related processing. So far we have touched upon mostly the rubber processing in detail paints and adhesives we have covered subsequently earlier. But today we are going to look for how plastics and fibre are process and important processes related to the rheology. Again the concepts covered starting from plastic processing, extrusion coating of wires that means it is a kind of a cross head extrusion, extrusion of sheets, tubular blown film extrusion, thermoforming, rotational molding, blow molding, injection stretch blow molding process, fibre spinning.

Basically spinning and drawing is also lot to do understanding the mechanical properties like stress strain curves in order to assess how it will crystallize, how the property will be developed after it is spun. Then spinnability of course, and while spinning instability is one of the major constraint after beyond thickness basically, or diameter of the I mean filaments there will be a problem ok. So, that we will discuss and draw resonance. Capillary waves and Rayleigh instability are two major reasons where from after certain draw you will try to have deformities basically because balance of forces capillary force, surface forces by say by hydrodynamic forces how it acts on a small cylindrical filaments I mean with small diameter of course.

So, if you again want to read through the literature these are the some of the you know important keywords that you must look for some of them I already talked upon, but laminar fibrils structure I did not talk that for yet and draw resonance of course. So, let us try to have a bird's eye view on plastic processing ok, what are the important processing. So, it starts with the extrusion as I told you extrusion is a heart of most of the processing ok, it includes rubber plastics composites everything. So, extrusion obviously long uniform solid or hollow complex cross sections with high production rates and low tooling cost and it has wide tolerance basically that the as far as equipment is concerned its dimension of the you know extruded final product is concerned. Injection molding as I mentioned it you earlier is also a very very intricate process It's a complex shapes various sizes ok, eliminating assembly high production rate of course, toolings are costly, but it gives at the end good dimensional stability what I did not discuss I mean injection molding is also meant for metal to rubber bonded product.

Reason is simple while injecting you generate lot of surface and that surface can bind well with the you know metallic part provided you do the due surface treatment of it ok. So, of course, we are not taking into account at this stage. Structural foam molding foam is a large class of high volume material ok. So, large parts of high stiffness to weight ratio less expensive tooling, ok by with you can do at a low production rate of course, but it is a huge bulk you generate. Rotational molding I mean also of course, coined with rotational blow molding also large hollow shapes like you can make a bucket you can make a you know bottles and what not many structure ok.

And it is a low tooling cost, but again lower production rate relatively, but of course, you can make a large structure that essentially gives you the you know commercial significance. Thermoforming another shallow to relatively deep cavities sort of a shape you can give it. Compression molding even though we said it is a primitive one, but of course, so in many applications compression molding does not have really alternatives ok. Of course, you can make it a compression molding machine little bit semi automatic to automatic. Transfer molding also for the complex shapes is in between you know injection and compression.

And then processing of composites material there are definitely DMC, SMC you make it by laying techniques by different techniques I am not going to take it forward at this stage how to make the DMC, SMCs and composite with the, you know yarn wounded on the inside the different types of complex shapes on a drum how it is you make a cylinder hydrogen cylinder shape for example, low weight high capacity. So, in general if I look into that in general plastic processing there are three steps whatever processing it is. First is heat it to softening or melting depending on the process you are considering ok. And then second you try to give it a shape it can be either through the die or first you make a parison and then parison finally, you put it in a mold and blow it ok. Ultimately it is you know the shaping is done under certain constraints depending on type of, you know shape you are going to give.

And then finally, of course, once it is softens flown optimally with the, you know into the cavities of a mold or die and then you have to cool it and that cooling also is very critical depending on type of samples you are handling. If your sample is semi crystalline as I told you under cooling or cooling rate plays very very important role giving the properties ok. Think about when you draw a fiber draw a filament the primary structure of a fiber. So, once you draw it in that particular direction the polymer or molecules will try to crystallize more orient more. So, the anisotropy will be automatically introduced.

So, depending on your requirement you can maneuver by changing the cooling rate by changing the drawing draw ratio etcetera I will come over there. So, selection of a you know process out of all these gamut of processes you exercise it depends on the quantity and production rate ok. Dimensional accuracy and surface finish you want ok. And forms and details of the product and nature of the material of course, that there comes the rheology is so important there and size of the final product. But here again once again I thought that I will show you a I mean the anatomy of a extruder because extruder as I mentioned is one of the heart of polymer processing.

Majorly softening, plasticizing and throwing it to the mold or die you do by the process of screw I mean extrusion with the help of a screw and barrel that gives you optimum mixing plasticization it gives you certain sort of a how to get rid of the you know volatiles etcetera etcetera you can do it even the agglomerate; as I mentioned you have a strainer just above the breaking plate. So, try to see you have a motor then reduction gearbox then screw starts from here you have, you know hopper and then through the hopper it goes the screws are wide open there deeper channel whatever it is. And then it goes through you know 3 zones like feed zone, compression zone and metering zone and you have every now and then the barrel heating and cooling system. And then finally, you go to the filtering screen which is actually housed on breaker plate and then you have the optimum place where you have a room you try to have a more like a laminar flow. At this stage if you are still lot of viscosity constraint there you may have the gear pump or something like that to push it further.

As far as electrospinning is concerned up to after this you may have electrical forces to take it out of the die basically and that way you make it more narrower. and I mean narrow in the sense smaller diameter of the you know filament you get it. But anyway here you have a die and through the die length you know it exist and exit and it depends on the if the thermoplastic there will be some cooling facilities and if it is a rubber sort of a things it yet has to go through a curing unit which starts from infrared or microwave cure. So, you have a pre-cure have a certain dimensional stability and then it goes to the hot air tunnel and depending on the you know lines I mean curing time line speed will be decided and length of the tunnel will be decided and that's how you finally, get to have a final cure product. So, that's what I thought it'll be easy for you to realize and I gave once again little depiction on extrusion.

The second unit process is wire coating which is yet another extrusion process, but it is called cross head extrusion. So, you can see here the molten mass of the polymer where as I mentioned it to you earlier see if you want to make a bead of the tyre where wires are there if you want to make a cable say for instance this sort of a shaping operation is performed and then you have a screw and barrel or whatever you may have a ram also ram can push it. So, through heat it pushes the melt comes it submerges the wire goes the molten mass submerges and giving rise to coated wire basically. This unit process I will take it forward in one of those classes to give you a detailed depiction to, how to really correlate with the rheology and vice versa with the rheology how can you come up with a efficient design basically. Another example of is a extrusion of a sheet continuous sheet.

So, this sheeting has lot of implication in the form of a mat in the form of a you know building material it has lot of implication. So, it is essentially what it is your melt inlet is there and then you have a optimum you know melt distribution manifold and then through which it goes through the die land and finally, die you get it through and this is the side view of it how the machine anatomy looks like. So, again this two are very very important process for both homogenizing melting and giving it a final. So, those are essentially extrusion driven processes. Now, another unit process which is utmost important is a tubular blown film extrusion.

I mean you make some extruded films and there are some dedicated company of course, who works on making some sort of a film it can be a plastic film it can be even rubber you call it a sheet, but it can be a film I mean film and sheet there is not much of a discrimination except the thickness part of it. So, you see the entire unit you have a extrusion unit again or ramp unit whatever it is, it pushes the melt and the melt goes through a essentially a parison sort of a formation and you have a air here and the film is blown and then it actually finally, wounded up here. So, entire mass entire pictorial depiction is here the whole machine and starting from the feed as well as to the winding up unit. So, you are getting it here and it is wounded up. So, this is what schematically shown here and here you have the control panel through which you can monitor very closely what is the thickness you are getting, what is the every other things you are going to get it for the process, in-line off-line process, in-line process controls.

So, other part of it important process is a thermoforming it is a very simple process what you do essentially you have a thermoplastic sheet that you make it otherwise by extrusion process also and then that plastic has to heat in and soften and you have a mold basically and in that you essentially heat it and then try to suck it and then finally, cut it out and this is what it's the thermoforming process, huge structures, high volume production of polyurethane say for example, materials you can make it the by process of thermoforming. Another very important plastic processing you know technique is a rotational molding technique. So, rotational molding is again you have to feed in the mold the liquid, but what it has two axis where it rotates and it tries to you know form the this sort of a structure huge tanks, buckets these are used in you know roadways you are very familiar with. So, those structures which has a rounded structure basically are made by rotational molding technique. So, if you just go through the unit process let be depict one by one pre measured quantity of course, of the powder plastic powder placed inside the warm mold it can be a granule also, but powders are preferred because it gives you a better heat transfer and quickly gets molten, rotated on two axis inside the heated furnace, low equipment costs, longer process time, trash can, boat hulls, those you know aquatic sports and all you might have seen those huge structures are made toys you know footballs which has a rounded shapes you can even make it by that process and wall thickness can be typically 0.

4 millimeter or so and also the slash molding is another part of it component of it. So, the mold begins rotating biaxially and it transferred it into oven that's the process done the mold continues to rotate as a resin melts and coats the wall of the mold. So, from inside it goes outside of the mold actually I mean outer part of the mold and the mold is cooled until the resin hardens I mean resin it may be, you can interpret as a plastic mold melt also resin in the sense if you want to make it just in case some composite structures by rotational molding composite structure is also possible. So, that is how the resin is the compounded resin basically and the rotational is stopped and the mold is open to remove the finished product. So, that is the unit process.

In general blow molding is another technique which is also very unique of its own. So, for manufacturing again hollow articles such as small bottles for household products, breweries, personal care, dairy products, containers for industrial goods or chemicals, fuel tanks, drums, car dashboards and so on. So, small volume to large volume I mean bottle to you know car dashboard part of it you can imagine I mean it is a huge ABS dashboard I am talking about. So, you can see simply it looks like this you have a again the blowing pin here and then you first form a parison and that parison is actually blown through the blow pin and then finally, you get the shape here. So, this is A B C D that is how the process is actually completed.

So, the depiction of it extruder heat with the blowing pin and open mold and extrusion of the parison step B. Step C here you can see it from here mold closed and parison pin in the bottle and sealed from the top. Now, it is a closed sealed from the top here and then the inflated parison forming a bottle and cool it down and eject it out that is the unit process look like. So, it is actually it is shown like a you know I am showing you like a batch process you can make it a continuous see it comes over here and then it fills and the parison goes and it gets blown up and then finally, here eject it out and the whole cycle continues, one after the other as a continuous process like I depicted while talking about the injection molding process. But there are certain tricks certain program by which you can make the parison.

So, suppose if this is the structure depicted here a bottle structure you just imagine there you need to have a certain in the make of the bottle certain thickness because where you have more stress you need to have more material there. In the middle of that you may be needing not that much or at the end bottom of that it will be bearing load. So, you have a differential thickness that you have to give. So, what you have to do you have to program in such a way making a parison that there are different thickness you can see here this is one let us take a arbitrary unit here this is that is ultimately blown to 0.

034. Similar so it is 0.084 that is blown to 0.031. So, accordingly whole portion of it has to be programmed depending on the final structure you are going to it is interesting making the partition there as a trick basically and their rheology is very important how you make it and given a parison structure basically initial partition structure of it. So, this is what it is. But injection stretch blow molding is another process it is interesting process.

So, what happens see that it's a two step process essentially however, people try to make it in one step. The preform is molded cooled and transported in the you know stretch blow molding unit. So, here you can see through the extrusion again you make the parison and that parison is taken out here in the next step you put it in the mold, mold is closed and at this juncture you are trying to stretch it little bit and then after stretch you are trying to give a final blow and you get it. So, that is what it is, but in order to save time and from the thermodynamics way, energy efficacy way sometimes it is being done in one step single step itself. That means, you give make the parison there itself you try to blow stretch and blow it.

So, of course, the perfection in the two step process is much more compared to the single step process. So, there lies a trick there lies a you know design complication. So, let me read it out it will be easy for you to grasp it. Two step process the preform is molded cooled and transported to the stretch blown station. So, it is transported here and then where it is reheated thermally conditioned to a temperature Ts, Ts is a softening temperature do not take it like a melting temperature it is well above melting temperature.

And then stretch it with an axially moving rod while simultaneously being blown in the mold. So, two things a pin comes and then that tries to stretch and after that you try to blow it. And in one step process as I mentioned preform is cooled to stretching temperature Ts and then stretched and blown in the same molding station to confirm the shape of it. I told you the I mean comparison between single step and. So, if I try to see diagrammatically see if you see here temperature in y axis I mean it is indicating melting temperature Tg and in between of course, the softening temperature near about this region that I meant to say.

So, this is the room temperature lies. So, initially you are heating. So, molding is performed above Tm as usual always plastic molding you do it at a, you know more than the Tm at this 10 to 18 degree more than the melting temperature. And then you rapidly cooled it come over here it is a softening temperature. So, in single step you finish it here in one go while in the two step process you take it forward cool it down in the room temperature then again reheat it and finally, the processes are depicted that way you do it. So, there is definitely there a thermal history will be different relaxation part is also different.

So, here material in two step process is optimally relaxed after the fast performing. So, thermal stress will be relatively less and you will have a more perfection as far as article you are getting by two step process by injection stress blow molding steps. So, now coming to the fiber processing I mean fiber I am not going into the, you know secondary tertiary processing like say for example, for fiber as I mentioned it to earlier also the first basic unit process is making a filament. And then from filament you make a yarn from the yarn you go to the you know thread ok. And this thread or yarn you can go for weaving you can make it a two dimensional structure you can go for you know different other type of a processing melting and of course, you can make a continuous loop out of this you know filaments of yarns and making some some sort of a structure ok.

So, there are I am not going into that I am just let us concentrate on the basic unit process which is the filament making and that is what it is called spinning. So, in spinning is a just like an extrusion basically you again pump the material through very narrow clearances which are called spinnerets ok. So, the melt there are three types of spinning actually ok. One is called melt spinning, second is dry spinning, third is wet spinning ok. Depending on type of material depending on type of perfection or roundedness you want in the ultimate spun filament you have to choose one over the other ok.

So, the melt spinning of fiber begins with the melting and pumping the solid you know plates by a screw extruder normally it is followed by a gear pump. So, gear pump is important remember what I told you from the basic fundamentals fibers are more crystalline number one. Number two they have a intermediate molecular weight if you just compare rubber, fiber then plastics. So, obviously, they have a higher viscosity than that of a plastic extrusion case. So, you may be needing some gear pump to additional pump it forward through the spinnerets, Remember spinnerets are very narrow holes ok.

So, you have a huge pressure drop pressure issues there ok. So, you will not be able to make them shown otherwise and you can consider those spinneret holes single single as a die small little rounded dies ok. So, that is what the spinneret is. So, three unit processes are pictorially depicted the the again the through the filter you have to get rid of any agglomerate anything. So, you have a filter then it through the filter the melts goes through a spinnerets and it is pumps and then it is takes off and then finally, it is take off unit.

So, that is the total unit, but if it as long as dry spinning is concerned wet spinning is concerned it is not a melt molten mass it is all about the solution. So, you have a dissolve in some good solvent or the other ok. So, the first process which is called you know dry spinning ok. Here you know you dissolve it and then it it spuns and with the dry air or something you try to get rid of the solvent and cool it down with the dry air basically and then finally, wind it. But additional steps is involved in wet spinning you have to really dip it through a non solvent bath ok.

So, after spins it tries to get rid of the solvent that way and then finally, you stretch and blow. Of course, stretching is the integral part that I am going to depict you just now because I just shown you the extrusion part ok. So, after it comes out of the spinneret that's not all that does not give you a optimum crystallinity, optimum strength of the material it has to be stretched further sometime 20 times that stretching is being established I will go there ok. So, those whole things actually has a implication in terms of rheology ok. So, first of all it is about the flow, second is that semi-molten state it is a soften state you are trying to draw it basically it is it is of course, below melting temperature after that, but you are trying to draw it basically.

So, that is the process where the balance between the flow and crystallization plays very important role. And finally, what is the extent you can draw it for those instability parts take over as a intricate role. So, there are certain limits. So, after which the Rayleigh instability or other instability or capillary instability takes over. So, you cannot go even finer than that by a conventional process, but of course, so there are certain ways you can go down in terms of the diameter as per a spinning concern that unit process is known as electrospinning I am not going into the details of it for that I mean let us take it keep it outside the scope of this present context.

So, let us try to understand how we are doing it the unit process let us focus on, this is our just after spinneret it comes out here. Now what we have to do we have to get a with a pulley system differential speed. So, this is the z axis up to which it equilibrate now we will take off somewhere let us try to have this distance. So, here this is the v, the v_0 is the velocity, A_0 is the you know surface area of that and of course, you can assume it with the diameter if you consider cylindrical stuff and then vz is the actually where you try to make it it depends on the, how much you want to draw depending on that velocity will matter. So, here approximately it gives you a pictorial depiction very nicely see A/A_0 what is A is here the diameter finally, you are getting and A_0 is the initial you know area here.

So, area by area here in a reverse way radius by radius, radius over here let us say R, R_0 and radius here let us say R. So, now, we can see very nice with the distance from here to here that is z, z equals to 0 here and z are some values finite values 25, 50, 75, 100, 125 ,150, and with that you see is a very nice depiction between two polymers which is nylon 6 another is a polypropylene we are drawing it say optimum takeoff velocity of 300 m/min and close to that for polypropylene 350 say. So, now, you see how we can get a you are reaching with the distance optimum area by area it is almost stabilized after certain points you can see although 150 125 itself almost it is reached the optimum thing, but as far as radius is concerned it is a reverse way it is plotted and you see that there also you can get a optimization there. So, melt strand area and radius profile is very very important to optimize and that optimization once again is related to flow as well as crystallization I mean after certain drawing and finally, here you are you have constraints likes instabilities.

So, that you have to decide upon where to stop. So, a single strand emerging from spinneret undergoes die swell. So, that is depicted here because fibers are no exception this plastic material after all and then cooling to a point of solidification and drawn and takeoff unit that is what is depicted. So, that is the unit process one must understand. So, rest of the things are well depicted here you will be able to, but what is interesting basically depending on the velocity takeoff velocity its crystallization will be different. So, let us try to understand one thing we try to roll up after stretch it say melt is here and melt is gradually going down with the stretch and you see at a particular point if you try to analyze at different velocities see how the structural changes happen because of the nucleation and growth process at a very low speed of drawing you see is a holes all spheroidic structure.

Then at second stage you have a low not very low this was very low, very low extrusion rate and second step you see it is a rotated nucleated twisted lamellar sort of a structure it forms. And then in that the third stage and fourth stage, you see maximum occurrence of nucleated lamellar untwisted sort of a structure it forms and schematically you see that is what is exactly happening depending on your stretch your alignment. So, this is what it actually matters and that is manifested ultimately with the strength of the filament you are getting same material spinning, but depending on the velocity depending on these your structure will be different internal structure morphology you call it. So, that is also very important alongside with understanding the you know rheology of the material. So, now you see you just try understanding a general stress-strain behavior of a semi-crystalline polymer.

So, as you see a dumbbell is depicted because normally we do test it with a dumbbell as per the ASTM or other standard test methodologies because it takes care of, you know force distribution or force imbalance basically. So, otherwise it will not be concentrate within the area of interest say within the we call it gauge many times that is what you look out. So, there is a yield point I already depicted you and then if the draw starts. So, after yield point if you go it the molecules tries to draw, but let us try to understand frame by frame what happens I mean we are going to the molecular models depicting the unit process in terms of crystallization. See you have a lamellar sort of a orientation lamellae means I mean whatever belongs to the crystalline zone and there are certain amorphous zone.

So, in between molecule links up because one molecule cannot remain perpetually in the you know same crystalline form. So, there will be tie molecule no man's land and there will be some amorphous part of it. So, if you try to go if I go to the more and more stretch what is happening let us go step by step this is the number 1 or a the lamellar slip rigidly past one another and lamellae parallel to the direction of the draw and cannot slip. In the b stage it reaches when you are further drawing it what happens at this stage at which necking begins and strain is accumulated almost entirely by the inter lamellar amorphous component of it. And then since amorphous tie is tie molecule that is that is giving a junction between the crystalline and amorphous part which is you can you can say it is a semi or quasi crystalline sort of a, you know environment that those molecules belong.

And since the amorphous ties are almost completely extended now they do not have any scope now for sure it will be concentrated to the crystals. So, amorphous is oriented already tie started orienting. So, you have no option other than it goes to the lamellae to break up. So, that is what is happening exactly lamellae started breaking up and it goes in the finally, the fragment slips further in the direction of the draw begins more and more aligned in those fragments basically. And that is the ultimate part you get it and they are now from five regions of alternating crystal blocks.

It is somehow like it shows like a blocky structure amorphous crystalline tie molecules are pretty much quasi to little bit more oriented structure it gains and it move belongs tries to belongs to part of the crystalline part of it. And that is how the whole it is a it is a all together a whole research domain where you can really concentrate in terms of viscoelastic property in terms of elastic property crystallization and growth. Of course, rheology matters because still the molecules are not in the frozenly orient, I mean it is not orientation is not yet frozen that's why upon stretching we are getting those.

Spinnability is important I mean there are certain molecules you may be having some exotic molecules, but still I mean you cannot make a fiber out of it filament out of it. Even in fact making aramids initially was difficult, a liquid crystals which has certain orientation to spin them optimally to make a filament it is a tall task.

So, Spinnability refers to the ability of a polymer melt to transform into the long fibers and to be drawn to large elongation that is it is able to span easily and stably without breaking. And Spinnability arises due to the typical coil molecular structure of the long chain molecule which tends to uncoil and stretch that is what is exactly happening there initial face. But ultimately it, it extends that orientation part to the even lamellae crystalline component of it also. The high extensional velocity that is very important unless you have a high extensional viscosity if you draw it it will fail essentially. Because what try to understand what you are making when you stretch it you are trying to make more surface area.

So, unless you have a viscosity barrier I mean surface area will try to minimize. So, it'll try to fail from there forming spin out all small you know where you have a minimum surface area you all know spheres are having minimum surface area as compared to a stress cylinder. So, of the melt gives rise to extensional force and which exceeds the surface tension force giving which. So, up to that boundary condition when your viscous force is dominant predominant over you know surface tension force you will be still able to draw it as a smooth jet basically after that it will be a failure. And there are different types of failures one of the failure reason as I mentioned it to you that is this by and large depicted in instability basically.

So, instability is always associated with high speed polymer processing like film where surface area is important film casting film spinning and in melt spinning following types of instabilities occur one is called draw it is called by and large draw resonances. And this causes a periodic fluctuation of cross sectional area take up. So, that is the limit you reach to you cannot after I mean beyond that and this results in thinning of strand close to take up rows and thickening away from it. And it gives giving rise to which has a thick and thin regions occurring alternatively. So, you do not have a very continuous rounded of same diameter structure any more after that.

So, there are lot of factors as I mentioned it you to escalate or to pacify this instabilities the temperature of course, of the fiber rate of elongation is utmost important the air drag and rate of mass out that means, as only the take up rolls speed is controlled not the strand diameter. So, those are the some of the factors you must know. So, this particular things gives you a rough idea about the draw ratio, draw ratio is again the ratio of the diameter initially spun and then finally, what you are getting that is called and there are limit and that limit is called critical draw ratio after which your instability everything will happen. For Newtonian fluid it is around 3 you get it beyond that unstable, but of course, for non-Newtonian fluid there lies advantage which fiber material polymer material fiber forming polymer materials are you can go as high as like 20. So, there are certain formulas correlating the basic parameters like you know a dimensionless number like n where L is the spin line length g is the tensile modulus k is the consistency index you get it from considering a pseudoplastic and v0 is the spin rate velocity.

$$N = 3^{(m-1)/2n}\left(\frac{k}{G}\right)^{1/n}\left(\frac{V_0}{L}\right)$$

So, here depicts dr versus your dimensionless number and from this stable unstable areas you know unstable areas depending on the stability instability analysis you will be able to pretty much optimize what should be the optimum draw ratio for a given sort of a problem. So, again melt fracture as I mentioned at you plays very critical role here melt fracture is also known as instability that way associated with the die flowing polymer you know melts and that can appear as a die swell, shark skin, ripples or sinusoidal distortion, bambooing effects as well as severe distortion. Severe distortion also I already shown you in the earlier classes while elaborating different types of artifacts that happens in the form of melt fractures. And failure consideration considering the fiber spinning cohesive or brittle fracture, necking or ductile fracture capillary wave instability. So, draw resonance is not the cause of any failure or breakage of the filament, but causes a periodic variation of the you know diameter of that.

So, capillary wave or Rayleigh instability since I mentioned it has lot to do with you know fluid jet and you are trying to draw it after a drawing again it is a balance between two forces one is a cohesive force that tries to keep the molecules intact. And second one is the hydrodynamic it includes the surface forces also and that is responsible breaking it down. And this ratio again is called capillary number ratio between the two such forces and that decides what will be the breakage point. So, you are trying to draw it at certain point trying it will try to form a spherical droplets basically. So, that is how you can calculate it and maximum uninterrupted jet there is a length you can you can calculate with the capillary number and Reynolds number and those are related with these equations.

$$Z^*_{cap} = 12d\left(Ca^{1/2} + 3\frac{Ca}{\mathrm{Re}}\right)$$

where, the capillary number $Ca = \upsilon^2 d\rho/\gamma$
and the Reynolds number $Re = d\upsilon\rho/\eta$

And there are different equations also, but this equation is very very good relating the physical properties like velocity, density, viscosity, and surface tension of course. And as the melt starts you know coming out of the holes of the spinneret, what are the phenomena happen formation of the droplet and liquid jet which can sustain the wave at the interface and complete atomization. So, these are the some of the unit processes that it happens beyond. So, again this is little irrelevant, but still I will show you if you try to understand different fibers what are the properties you get it, stuffs like a rigid polymer as i mentioned like aramid it's very stiff, it gives you stress-strain property very very stiff less elongation still over here you can see I mean of course, we are not plotting the you know tensile strength, but we are plotting tenacity.

Tenacity is breaking load by linear density. So, that way aramid is more than the glass as well as steel because its density, after all linear density is far less. And if you consider other fibers like cotton, cotton has a low strength low elongation I mean low compared to viscous or modified form of it polyester or polyamide, nylon and polyester they are comparable of course, elongation way an initial modulus of polyester is high of course, the elongation or flexibility you get out of you know for nylon 6 and 6,6 is little more. So, I am not going into the details of that textile technology or textile part of it, but nonetheless up till now it gives you a fairly good idea about how to spin and spinning what are the consideration you have to make while designing a spinneret, while designing a take up unit and then setting up its you know temperature as well as tension how much force you should do what should be the velocity or what should be the optimum draw ratio, upto which you can process it. So, that is it gives you I suppose a fairly good idea about the basics of processing. So, now, it will be our so a transition from beginner to intermediate I believe you I already made you up to this and that second stage will be to the you know experts I mean little bit more ahead of it.

So, for that we will try to understand the unit process and try to correlate with the rheology then as the challenge being a design engineer designing a process tool or designing a you know, how the process condition you should have to have a optimum you know formation without any defects and all. So, we will try to show you at least one such example with the extrusion we will take it forward to the you know expert level and we giving some basic consideration, but nonetheless as I mentioned in this particular lecture there are still scope to upgrade it depending on your your request and your kind of a participation we will like to make it add on the to the expert level ok. So, that is it what I gave you today in a nutshell talked about the plastic processing and the essence of it and essence of fibre processing. In the next lecture we have done a whole lot of processing we will try to solve numerical problems related to processing.

So, that you will be little bit more you know confident ok. So, at least something on the mixing, something on the extrusion, something on the injection molding we will try to grasp it. So, that will give you some fairly good idea with that. Thank you very much.