Rheology and Processing of Paints, Plastic and Elastomer based Composites

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Lecture 43: Wire coating, Garvey die, Profile Extrusion

Welcome to NPTEL online certification courses on Rheology and Processing of Paints, Plastic and Elastomer Based Composite. We are on penalty met week today that is week number 8 and its selection number 8.1. So, it all about wire coating, Garvey dye and profile extrusion. So, so far and so forth we we try to give you light on rheology and followed by processing ok. And in processing site I tried to emphasize upon the you know extrusion.

So, extrusion is one of the heart of the process and part of the either extrusion as a whole for as a shaping operation or it was omnipresent in the form of injection molding, blow molding as a conveying plasticizing that kind of thing. So, understanding extrusion process is one of the fundamental challenge in polymer technology basically. So, today I will try to show you one or two processes one is wire coating another is profile extrusion. By the conventional design technique and then and then try to show light on what are the complication in terms of design happens.

And next subsequent I will try to take you computational design and how do you really do it with a standard one of the commercial you know softwares ok that I will show light and some of the results of our research that I will try to share with you. So, that you can also practice subsequently if you are from industry in the industries or your academics you can better practice in the research ok. So, the first thing is covered will be wire coating as I mentioned it you wire coating is sometimes known as you know T-head extrusion of you know. So, a wire is coming wire or a thread will come and then there will be a polymer flow line will submerge on that. So, that at the end you have the wire coated with the polymer films or polymer you know cover shift.

So, applications you can find application in cables and in tire also in the form of a bead, and also in the convey belts you find application where wherever it is necessary ok. So, essentially the rubber will be reinforced that way with steel inside. And second we will try to analyze the problems very carefully the wire coating extrusion. We will try to see again velocity profile that I showed you how it happens actually. This is the first part of it.

Then we will move into a very traditional concepts exist particularly in our industries. While you make a compound and try to make a profile how good that compound will be for extrusion or you try to judge the feasibility of extrusion developing a compound ok. So, that is what is called Garvey dye that takes care of actually dies well and surface roughness together that is very interesting. So, it has implication in profile extrusion and I will throw light on combination of profile extrusion say you have two different thickness two different materials coming together giving you a continuous sitting material and different types of profile dies I will elaborate on ok. But again the perception will be from the point of view of rheology and subsequently the design how we make it how you optimize it ok.

You understand by now extrusion as such is a multi parameter problem it is not a single parameter say you change the velocity, you change the pressure drop, you change the volumetric flow rate you come up with the optimum design no. So, I would like to make you understand subsequently the configuration of the process. I am not going into the details of it these are the some of the keywords as I give you of at the beginning of any lectures. So, these keywords will help you looking quickly through the internet through the books bibliography. So, some of the essential terms involved here in ok.

So, now try to understand first a unit process. So, what you have you have a payoff unit where from the spool the wire will come at a definite alignment of course. So, then the wire has to be little preheated and then through the extruder there will be all together extruder line that will submerge essentially and to have a coated wire basically. And that coated wire depending on the situation if it is plastic coating you just pull it down if you have you are shaping it just like a making a bead. So, you just pull it down ok.

But if it is a you know thermoset you are extruding then there of course, will be a vulcanization what a tunnel or whatever I talked about and then final let up or take off units. So, that is how you make a long continuous you know wire coated with polymers. So, now there are different types of dies possible ok. See how it actually works let us try to understand from this cartoon you will be able to understand how it works ok. It is called pressure type die.

So, pressure type die wire coating die is a annulus basically ok. And the side surface of which is the wire to be coated. So, wire is coming out as you can see and moving at a constant speed. And the flow through this type of die is analogous to the flow through the annulus formed by coaxial cylinder. See here from the melt polymer melt enters through the extrusion extruder extrude and it submerges essentially and finally, you get to see a coated wire ok.

So, that is the process. Now so far so forth I was talking about as if one polymer was coming out and trying to coat. And you understand the cable, cable can be consisting of not a single wire or fiber, it can be multiple wire also. So, based on that type of design you want to make for cables or bead wire ok. So, it can be your wire is inside a matrix and that whole thing is coated you see yellow and red color representing two different polymers here.

It can be either way it can be wire inside or whatever hollow part inside and then you have subsequently two I mean not only not hollow in this case, wire in the middle of it or it can be in the other form also. This all are possible with a cable coating extrusion. You see there is a wire is coming out whatever preform it has ok. Then then yellow and red through two different channels by extrusion process these are coming out and they are converging and so that ultimately to a concentric annulus manner the axially moving wire will be coated by two submerging layer, but of course, try to understand the complication of the problem. See two wires are coming wire is coming ok.

So, it can be either wire is moving at a speed and these two submerging layers also moving at the speed. But suppose if you want little bit of friction so that you would like to have a more sort of a bonding with the wire then you can afford to have little difference in terms of speeds as well. But of course, when you have a multiple layer this is very important or otherwise one polymer if it does not really sufficiently cools down there will be I mean intermixing happening. So, there is no definite boundary as you can see from this cut will happen. So, this is also very important from that point of view.

So, let us try to understand this whole process I mean we are trying to make our analysis confined here. Let us for the time being have a one flow channel and one wire ok. So, we will try to understand the entire process, but before that we must make some before understanding velocity and stress distribution ok we must have certain assumptions. So, what are those assumption? We are we assume flow is in steady state condition first thing ok. It may not be steady as I mentioned it to earlier there will be several eddies vortex that might form and that you we assume taken care of with the entrance angle, with the type of material it's a you know friction between the you know metallic component with the filler slip part of it is well taken care of ok.

The polymer when flowing a power law model through a sufficient long cylindrical die in which wire moves along the concentric at a constant speed. So, that you are assuming here. The flow is laminar and the velocity in the radial direction is negligible ok. Small compared to the axial direction. So, for the momentum point of view we are taking in a one direction say z direction here ok.

So, inertial effect is negligible small compared to the viscous effect. So, viscosity dominates obviously, which is reasonable going to the very high viscosity of the polymer. And then the heat conduction of course, because you have to take thermodynamics also into account thermal part also into account ok. But heat conduction flows is negligible small compared to the radial direction. So, it is all in radial direction radial means this direction and this is the axial direction ok this is the radial direction I can see the r here.

And the melt density specific heat thermal conductivity are independent of temperature it says through the channel it is constant it is not varying and the gravitational effect is also negligible. So, these are the few assumption based on that we are trying to analyze the problem first clear. And then under the assumption this assumption above using the cylindrical coordinates cylindrical coordinates you know it often makes it simple for the analysis. So, we try to say dp/dz which is axial pressure gradient and sigma rz it should be subscript of course, rz is the shear stress component of it ok. And then you can figure out a relation very easily from the momentum balance point of view ok minus dp/dz equals to 1 by r d/dr r into sigma rz equals to 0.

$$-\frac{\partial p}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}(r\sigma_{rz})=0$$

And from the energy balance point of view so what you have you have two components one of the components is conductive another component is of course, is the viscous heating as I mentioned it to you ok. So, that'll give rise to a I mean total heat rise ok and that consist of your Cp part your you know rho part etcetera etcetera thermal diffusivity part into account. So, you can see this is the viscous shear heating component of it so this is the heat balance ok. So, now certain conditions you have to put it for non-isothermal operation must be solved under such certain condition r equals to k into r0 although these are the limits of 0 less than z 0 that is the that is the typical regime we are considering vz equals to vy. So, here we are assuming velocity of the polymers melt which is submerging the flow and the wire is some and t equals to t wire.

$$\rho c_{\mathrm{p}} v_z \frac{\partial T}{\partial z}=\frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\eta\left(\frac{\partial v_z}{\partial r}\right)^2$$

So, similarly second assumption r equals to r0 then this length t equals to t wire. So, these are the some of the parameters you can you can read through. And if you try to you know put a adiabatic conditions ok the wire surface and the die wall and the boundary condition given by these are the conditions ok. So, this is how you solve it for these two equations. So, I am not going into the thermal part currently because thermal part I am not taking into account this, but nonetheless the shear component of it can be represented in this form ok.

And then in order to obtain a velocity profile one needs to choose a rheological model that I told you I mean you can either you know solve it for a Newtonian equation or Power law. Power law is much easier, but as I showed you realistic fluids say EPDM profile extrusion you are talking about. It fits well with the Carreu yasuda type of a model and which is actually 5 parameter model. So, that solving analytically is very difficult from solving this differential equation then literally you have less number of equation you have more unknowns. So, in those cases you need simulation or you need sort of a you know computer aided solver basically to solve it for that also I'll show you with some of the solver some of the platforms.

So, nonetheless what I taught you the two important thing one is pressure drop another is volume flow rate. So, that is very important. So, you can quickly arrive that with this set of conditions this is the volumetric flow rate that you can easily derive. So, you can calculate draw down ratio also. So, H is the thickness of the coating.

So, accordingly it transforms with the those dimension of the core dimension of final wire coated. So, it reduces that two parameters the draw ratio part of it. So, now so quickly the dp/dz you can see the pressure gradient plays very important role. So, for a given problem say you are considering a flow for LDPE wire coating problem. So, you can see the pressure gradient decreases as the wire speed increases q is the volumetric flow rate here indicating the drag flow becomes increasingly important as the wire speed increases.

$$D_R = \frac{{R_0}^2 - {R_i}^2}{(R_i + h)^2 - {R_i}^2}$$

$$\sigma_{rz} = -\tfrac{1}{2}\varsigma r + c_1/r$$

$$Q = 2\pi {R_0}^2 \int_{\kappa}^{1} v_z(\xi)\, \xi \, d\xi$$

So, that is the balance. So, similarly if you look it at from the exit pressure point of view. So, you try to plot exit pressure with that volumetric flow rate for same LDPE with two different wire speeds say 2.46 and 7.55 at 240 degree centigrade and at a wire speed of you know 7.

55 millimeter per minute. So, one case you can see the 7.55 other is 2.46. So, p exist is decreased as the wire speed is increased and also the melt temperature is increased. So, that kind of a profile you can generate at different temperature of extrusion.

Remember with the temperature you are playing with the viscosity of the flow. So, hence the volumetric flow rate. Now, as I mentioned it to you the velocity profile, velocity profile apparently if it is a pressure driven flow you remember in a channel I talked about a parabolic flow profile ok, but unlike you can see it a wire is at the middle. So, if you can make it half half symmetrically you see now if it is only the drag flow consideration. So, wire is trying to pull it the molten mass in the front.

So, that way the pressure I mean that kind of a drag flow will take that kind of a flow ok. So, so if I if I draw it from here also you can expect another one here correct. So, in a similar show if I just try to combine these two your flow becomes little bit of asymmetric ok. So, if you combine pressure and drag and that is exactly what is happening inside. So, this I wanted to show you just to understand the complication of the velocity profile unlike it is all uniform in a cylinder through the cylinder when a only polymer melt is flowing, but in this case that complication is there ok.

So, up to that I will talk about because after that we will try to take it forward for the computational part. Now, the second part of this today's lecture is a Garvey die. You must be wondering what is Garvey die ok. It is as per ASTM 2230 possibly D 2230. So, this is the Garvey die produces a profile with four different angles you see this is the die shape.

So, 1, 2, 3, 4 you have four angles ok. It is not a symmetric extrusion ok which looks somewhat like a scaled down version of half of the thread. So, it originated from tire research essentially ok you know thread part is extruded ok. A rubber compound will with better flowing properties will give smooth profile obviously, and which with no defects even in the small corners. As I mentioned it to you earlier corners are the point because they are rubber is undergoing maximum deformation. If deformation is maximum the die swell is going to be maximum.

Shear rate is maximum that is going to be maximum deformed ok. So, it takes care of those intricate corners ok with no defects even the smallest corner that you have you look out a good extrusion will be ok will be no defect at the smallest corner acute angles basically. Conversely a back flowing rubber compound will show an uneven ripped and swollen profile and the quality of the extruded profile is ranked in a ranking system described in the ASTM standard and I will show you how it works. This is the Garvey die. You fit in on a single screw extruder and try to extrude your material your compound.

Here in three different types of I mean rubber compounds with variegated types of fillers in one case N339 you see high structure ok. Another case N326 lower structure comparatively another is even lower particle size and low structure are compared. I mean assume the loading is same rest of the compound formulation is same based rubber is same. As you can see there are three things swelling, edge, surface corners. So, accordingly it is ranked 1, 2, 3 that is a rating system and of course, the edge and surface.

You see in the first one that means with the high structure one carbon black is a profile is, all giving 4 out of 4 in terms of swelling, edge swelling 4 means minimum swelling and then edge surface corners edge is how smooth it is. So, edge is 10 here you can see 10 out of 10 another ranking system and surface is A. So that way is gives you the best. While on the contrary when you have the same average particle size high abrasion furnace, but lower structural variety you see here at the edges it is very poor. And the corner also it is very poor you see it is giving only 2 while it is 3 at least the swelling on the surface point of view and N234 is also bad that way I mean it is better than this, but not whole lot good.

So, this way even if one person who does not know much of the extrusion parameters rheology also, but he has to do extrusion over and over just simply after compounding just putting it and go through the ASTM standard ranking system he can decide upon if at all his compound is good to take it forward in the soft floor for the profile extrusion is it not very interesting. So, that is why this garvey die is very quite popular in rubber industries for practicing rubber technology even in the tire industry which is the gigantic part of the I mean major part of the tire I mean rubber productions there. Now, when I talk about the profile extrusion a profile may be a flat it can be like 2 different crosssections here you have seen circular cross-section you have a rectangular cross-section. It can have a rectangular itself hollow I mean particularly for car and all automotive you have that kind of a profile particularly with the EPDM I mean it's you do it on and on, doze top, ceiling material etcetera. So, there can be having different shape and particularly it can be U type of shape.

So, these are in the refrigerator and vehicle gasket window liner this type of complex cross-section or corrugated sort of a you know profiles are taken into account. I will take it at length in the next subsequent lecture if you have a closed loop structure open loop structure there can be a kind of a rotation introduced. So, that it will be distortion. So, how to take care of that those aspects, but in this case let us consider a profile which has a thicker little bit thicker you see it is 1.1 both left and right, but in middle it is thicker that kind of a extrusion how to design the die there lies a challenge.

In profile die design the most crucial problem in flow balancing that is to have uniform outflow velocity. So, it should not so happen you have a more opening here. So, obviously flow is more wherever you have more opening the fluid will always try to love to flow through that. It happens in your common human life also when you have less resistance you try to prepare that. Similar so if you have a narrow channel flow is going to be constricted.

So, that is the very reason a product with multiple local thickness is a challenge. Since polymer melts have a overwhelming tendency that is what I told you to flow through the area of least resistance and the melt flow will be higher velocity in the thick gaps. And you will be simply wondered to obtain a quantitative understanding of this consider the simple schematic figure in this figure particularly showing a die which has a central section at least 10 percent larger the larger gap. So, 1, 1.5 10 percent at least from the flow between the two flat plates analysis average velocity of the each section can be I will show you how it changes within a short while.

See this is the let us try to understand velocity into you know h1 and h2 let us consider this is h1 this is h2 I mean let us try to I mean that is the engineering you do always if you have a structure you try to figure out the where the symmetry you take analysis with the one half other half you just sum it up. So, we are taking the half of it and trying to analyze the velocity of it. So, average velocity for a power law fluids takes this form I mean with certain approximation let us assume it. Now try to understand the velocity ratio between the fluid is flowing through two different cross section one is wider h2 one is narrower h1. So, this average velocity you can easily calculate v average is 1.

$$V_{avg} = A\left(\frac{H}{2}\right)^{\frac{1}{n}+1}$$

21. So, while gap was only 10 percent larger. So, h2 is moving at a 21 percent faster. So, that does not. So, you understand it scaling up basically that is why I said overwhelming. So, you have to take it into consideration.

So, that velocity remains constant. If you have the same die length same die angle you end up in a trouble got the complication of it. So, similar so if you try to take a power law fluid it is going to be even worse let me show you. If n exponent is 0.33 instead of Newtonian fluid weight which we assume n equals to 1 so far up to this and this figure becomes 1.46 that means what? So, it is 46 percent higher speed in the wider channel.

$$\frac{V_{avg,2}}{V_{avg,1}} \sim \frac{\left(\frac{H_2}{2}\right)^{\frac{1}{n}+1}}{\left(\frac{H_1}{2}\right)^{\frac{1}{n}+1}} = \frac{1.1^2}{1} = 1.21$$

$$\frac{V_{avg,1}}{V_{avg,2}} \sim \frac{\left(\frac{H_2}{2}\right)^{\frac{1}{n}+1}}{\left(\frac{H_1}{2}\right)^{\frac{1}{n}+1}} = \frac{1.1^4}{1} = 1.46$$

So, this you can now anticipate what do I mean by rheology here. So, Newtonian to power law that to changing the index significantly varies my flow slightly make sense. So, this challenges they are in the design that the local channel gaps and end of the extruder to the die leaves that angle also by the way. So, that the thickness average outflow velocity remains same. So, you cannot afford to have 46 percent rise you cannot afford to have 21 percent rise it has to have the ratio 1 that is a challenge as a design engineer.

So, that you have to take care in your die design component of it. So far up to previous you know lectures I was just concentrating on the metering zone, metering zone eddies, get rid of eddies here we are into the die land, but still we have to give a consideration understood. So, let us try to see how we solve it this classical problem. See we will take a very simple design die design forget about the complications that you ultimately will be having for a actual profile extrusion. I have a circular cross section here rest are all it is a slit. So now, for a rectangular cross section I showed you a refer please refer to professor B.

R. Gupta's rheology book there is whole analytical solution is given. So, you can very easily calculate average velocity in the form of this again I have taken into consideration a power law fluid is the power law exponent in terms of pressure than you know all geometries it has. In a similar fashion flow through a circular channels will give you this solution. So, this is your assignment, assignment not the you know formal assignment to in order to better appreciate what I am talking about you have to really go derive those referring to professor B. R. Gupta's book and try to solve this and try to better realize how difference is going to be the velocity.

So now, what is our challenge? We have to make this velocity equal that is the classical challenge. So, if I have to really make this is the scaling I am getting ultimately. What is the scaling? Scaling is in terms of die length. You see here pictorially depicted if this is the length die length we call it I have to have a this additional length. So, that excess flow can be nullified here that is one of the way you can solve it.

Another way how do you solve it? You try to have a angular entrance another way how do you solve it? You can have material with different frictional coefficient with the polymer melts. So, that your slip velocity will be different where there is less resistance you try to have more resistance. So, that is how we can appreciate that. So, adhesion has a role there, friction or tribology has a role there other than the fluid mechanics part of it which is simply dealing with the flow. So, if you combine that you come up with a better design of a die that is the bottom line.

$$V_{s,avg} = \frac{n}{2n+1}\left[\frac{1}{m}\left(\frac{\Delta p}{L_s}\right)\right]^{1/n}\left(\frac{H}{2}\right)^{\frac{1}{n}+1}$$

$$V_{R,avg} = \frac{n}{3n+1}\left[\left(\frac{1}{2m}\right)\left(\frac{\Delta p}{L_R}\right)\right]^{1/n} R^{\frac{1}{n}+3}$$

$$\frac{L_R}{L_s} = \left(\frac{4n+2}{3n+1}\right)^{n}\left(\frac{R}{H}\right)^{n+1}$$

Let me show you the implication of the angle, angle, angle I was talking about. See this is the die. This is just like a plus sort of a I mean I am sorry it should be continuous there should not be any gap this sort of a profile you want to make. So, this is the plate die. Again problem will be a symmetric fine no problem, but if what if I make one of the channels narrower another I am become making thicker another channel of different dimension.

I just break apart the symmetry then your real challenge will come. So, in this particular step die what it is taking care the step entrance remember this is a die land basically part of it. So, similarly there are certain die which is called steam line die. So, you are playing with the die land here after the die head this is the die head which fits into the last part of the extruder after the metering zone. So, this is also distinctive zone of steam line velocity you see it is step down.

So, here ultimately it has a angular entrance. So, these are the some of the ways you can really circumvent the classical problem that I addressed that is all related to a variegated flow having different set of resistance and that depends on that is driven by the geometry used to make ultimately in a finish profile extrusion. Remember one thing I did invoked here to complicate the problem if there is some wire inside some reinforcement there many of the profiles in automotive say door lock they have a wire there sitting that ultimately locks that gives the stiffness of it. And there may be one of the part foam that further complicates. So, I am not going into that complication classically a fluid flowing through different clearances having variegated clearances geometries concludes how to solve it.

Anyway I hope you understood the gravity of the problem with this. So, I thought the talk about the profile extrusion little bit before we actually go for the computational design part of it. Once again the classical book and on top of that here I am yes this is the book I was talking about I told you you do some of the assignment solving flow through a channel flow through a annulus two solutions for a power law fluid for a Newtonian fluid you get that a direct solution there. So, please stick to that there are certain numerical problems given certain number of parameters say two parameter models you try to solve it and calculate out the velocity volumetric flow rate pressure drop so on and so forth. And that will give you a set of confidence while dealing with the numerical problems. So, what I taught today basically two things one is the essence of wire coating and second one about the Garvey die and to make you understand how to take care of different flow at different places part of the die to have a uniform flow also out.

So, hopefully so this will help you better understanding the FEA I'm not going into the basics of FEA of course, that I will be using a platform which is already I mean which does FEA based simulation each point the flow pattern I am not going into that. What I want to make you by this training subsequent three lectures or one practical classes on simulation. So, that you can practically usually do yourself without having much of a problem, but I that this course does not guarantee you I cannot really teach you FEA as well as whole lot of CFD or from the code level to make the code is already there will be using ANSYS platform and try to show you subsequently one of the I mean CFD based FEA based CFD simulation to design a die basically with that. Thank you very much.