Rheology and Processing of Paints, Plastic and Elastomer based Composites

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Lecture 34

Introduction to Two-Roll Mill and Mixing on Two - Roll Mill 2

Welcome to NPTEL online certification courses on Rheology and Processing of Paint, plastic and Elastomer based composites. Today we are in week 6 and lecture number 6.4 with deals with introduction to 2-roll mill and mixing on 2-roll mill and this is the part 2 essentially. So once again the concept covered we will try to see today from the fluid point of view how it is processed particularly when the rubber passes through the nip area. It is little bit on flow analysis, elongational flow and heat transfer is very very important while deciding the cooling system, heating and cooling system in that as I mentioned and but also overall quality of the mixes that you get end of the day because if you do not do good to the heat transfer things can be scorchy either or it can be you know degraded or else if you try to do it at lower temperature the problem is that it will try not to form region 2 basically. So that is the intention.

So analysis of heat flow will schematically show although we will not go into the detail of the heat transfer process and heat balance. Mill processability effect of elastomers various parameters that I highlighted already but in terms of the specific characteristics including the failure characteristics as I mentioned that particularly when it passes through nip it has to withstand very large elongation and then bit on the Weisenberg number and some light on the dimension analysis and when mathematics becomes very complicated, engineers what they do you will try to see left and right parameter they do the unit balance or dimension balance and from the basic units you will be able to come up with certain empirical relation. So that is the best way to approach that problem in those cases when the system is mathematically complicated and no singular solution you get it affirmatively. So keywords once again I am not again trying reading through every part of it but nonetheless if you just try to look through the literature these are the some of the keywords but what I told you the same book is actually the best was 2-roll processing by, you know B.R Gupta of 2-roll processing of rubbers and on top of that we have taken something from J.L White book basically and that is considered as I mentioned Bible of the rubber processing. So let us try to see the flow analysis how it can be done. The flow of material in the nip area of a 2-roll mill is very very complex first of all it is not as simple as that as I described when I am considering in parallel plate, coneand plate or for certain other geometries because you have a pressure, you have a shear rate, you know shear stress you have a velocity of the melt that keep on changing continuously. I mean once it passages from the bank near to the nip, nip so is the rheological your I mean consideration has to be met and mathematically it becomes the problem becomes complex.

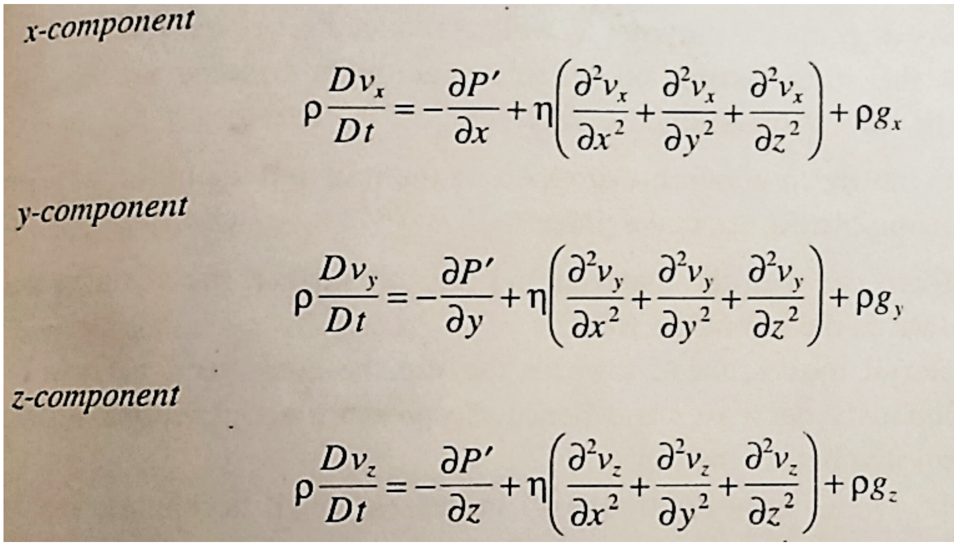
So let us try to analyze the flow around the nip area. So to analyze the flow behavior of rubber melts around the nip area it is necessary to use some equation of continuity and equation of motion. So it is a very common in any tackling any fluid mechanics problem. So the equation continuity relates to the rate of change of the mass per unit volume due to the flow it is a basically mass flow that is happening basically. Through the fixed volume phase and the equation of motion represents the rate of change of momentum per unit volume so mass as well as you know momentum balance you are doing simultaneously.

So if you see the equation of continuity in x, y, z three different direction your equation becomes takes d rho by dt equals to this type of form as I talked about later this will be del y actually and this is del z rather than subscript. So this is the equation you get it ultimately rho is the density vx, vy, vz are the velocity component three different and you can see that divergence of it and how it can be related to that this is what I was talking about the momentum part of it. So for incompressibility that is another thing you can impose that is the condition so this is the condition of incompressibility condition under isothermal of course we are not taking care of the local fluctuation of temperature by the way. We are imposing isothermal not the adiabatic condition here then it becomes little complex you have to consider the heat transfer part of it simultaneously. I will show you when we will try to talk about in the last lecture series lecture eight onwards, how to solve it in real life extrusion problem once it comes through and through the die.

$$\frac{\partial \rho}{\partial t} = -\left(\frac{\partial}{\partial x}\rho v_x + \frac{\partial}{\partial_y}\rho v_y + \frac{\partial}{\partial_z}\rho V_z\right)$$

$$= -(\nabla \cdot \rho \vec{v})$$

So, you can see those equations in three different component x, y, z this is the equations x, y and z component of it I already talked about I am not going back from the Navier-Stokes equation point of view but nonetheless if you just apply the incompressibility condition equation somewhat simplifies to this x, y and z direction. So the total time derivative becomes this is the form I am just making you familiar with the equations and your solver is going to solve ultimately unless you write the finite element code or fluid mechanical code from the scratch in a given package our intention is the very beginners level. So in the backdrop in the background your solver is going to solve this problem that you must have it in mind what type of equation it is trying to solve basically given the boundary condition etc. So flow analysis around the nip area the actual operation involves interplay of the machine parameters and physical variables like as I mentioned there are mill kinematics like roll speed obviously it is a rotational speed rpm nip gap friction ratio is nothing but the ratio of the rpm of two different two rolls and on top of that you have temperature pressure shear rate shear stress drag force material viscosity. So point is that this is a cartoon you can understand from here this is the bank area and the fluid flows from this direction to this direction we are not considering here at this stage which roll it will form the band actually elastic band.



x-component

$$\rho\frac{Dv_x}{Dt}=-\frac{\partial P'}{\partial x}+\eta\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}+\frac{\partial^2 v_x}{\partial z^2}\right)+\rho g_x$$

y-component

$$\rho\frac{Dv_y}{Dt}=-\frac{\partial P'}{\partial y}+\eta\left(\frac{\partial^2 v_y}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_y}{\partial z^2}\right)+\rho g_y$$

z-component

$$\rho\frac{Dv_z}{Dt}=-\frac{\partial P'}{\partial z}+\eta\left(\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)+\rho g_z$$

So as soon as the material is put on bank rollers is subjected the following what happens a drag force between the material and roll surfaces starts pulling it inward to that nip of course as I mentioned it immediately which is in contact it tries to you know pull it towards the nip however the middle part as I mentioned there will be some sort of a circulatory motion or kneading sort of action it happens. But for the time being you try to consider the velocity profile what it happens as the material moves towards the nip area the cross section of the fluid decreases progressively the whole this area becomes this small only so one at a time as I mentioned can go and progressively pressure builds up pressure becomes higher and higher just before the nip gap so here is the exit. So now again the material when it comes out you see again the considering it two rolls where we have made some approximation two rolls of equal velocity here we are not taking care of a asymmetry in any way. care of a asymmetry in any way. And then you see the parabolic velocity profile as you can see once it exists exit the nip so nip area something different story but after the nip the midpoint of it has acquired the highest velocity reason is simple the wall slip part of it.

The material thus continuously accelerates up to the nip point beyond which it moves with a uniform velocity so after that it becomes all uniform. And the pressure acting on the material falls into atmospheric pressure obviously whatever pressure it has it goes to atmospheric pressure. So this is the pressure gradient that it forms across its journey from the nip to the equilibrium position. So this is how the drag force you can calculate alpha is a arbitrary coordinate that I will show you when I show the whole velocity profile of it and that is how you can calculate out the drag force how much it is acting at any point of time. So that is how I am not without further going into the consideration some of the approximation we are making in compressible fluid under isothermal condition and flow is a steady state flow condition in the nip area.

So then we can have a velocity distribution like I showed you other days in this case particularly it takes the form the velocity distribution of it. Remember we have taken symmetric rotation of the roll no friction ratio with that you get this velocity line basically. So now for a Newtonian fluid we can see all these solutions basically this is the whole part of it from the bank inward inward inward then outward see the how the velocity changes first place. Initially as I said it will try to go inside more and it will escape after a while it is a convex I mean concave type of a velocity profile it gets. Then it becomes more at the roll because it is a drag force it is roll takes it along I mean middle one does not get that you know consideration that some point of time it becomes all velocity equal.

So this is the alpha beta gamma is a coordinate of it in the direction of the flow and once it escapes the nip area you have a parabolic flow again the central line it inverts exactly what was there it inverts and then eventually at certain distances become similar and then it finally forms a band. So this is the scenario all together it happens. So these are the some of the solutions that you get it for Newtonian and non-Newtonian fluids depending on this coordinates actually alpha beta gamma. So this is how we can calculate maximum pressure maximum pressure not necessarily it will form at the right at the nip position it may be somewhere little away from there. So that is where you get the maximum so that you can realize from here this so that is very interesting.

So asymmetric rotation equation becomes little modified of course and then asymmetric roll rotation means you are considering the friction ratio even it is even you know complicated. So these are the some of the things I do not want you do not get afraid of this looking at these equations but I am trying to see show you the overall picture of it. So that you understand the complexity of the problem some of you I am sure who are good hold on mathematics likes doing mathematics they can grasp it over and make it make himself or herself more expert so that to deal with the you know the solution of it physical solution of it. So these are the some of the symmetric vice versa asymmetric cases how the I mean this shear rate shear stress that happens. So remember one thing every point the shear stress shear rates are not equal it is changing with the coordinate that is what I mean by shear stress and shear rates in a machine like mixing mill or any processing machine its distribution it is not a single mixing mill.

So one hand it takes care of the distribution another hand it takes care of the dispersion part of it. So that much is sufficient for you right at this stage. So you can understand the how you calculate the z with the dimensionless distance not exactly at the center position but somewhere else you get the maximum pressure. If you do try to have a you know dimensionless pressure as a dimensionless distance plot it that kind of a things you get it and that you get it a experimental one somewhere here and the real equation with pseudo plastic fluid with pseudo plasticity index different one case one means what it is almost due to near condition or pseudo plastic condition so you can get it. Elongational flow also plays very important role so elongational viscosity has also significant part in that.

So similar way considering the velocity profile across the role you can calculate its elongational shear rate and shear stress basically. So again it is very complicated that way but very quickly try to understand heat transfer in a two role mill why it is necessary because remember in one hand we are applying very high degree of rate of deformation rubber being a viscoelastic material if you deform it it tries to get heated up because lot of hysteretic events will happen and second of all you add filler that aggregate break down takes place. So in a I mean in a sense it will give you internal heat generation once you shear. So even if you start with a very nominal temperature over time the temperature shoots out very fast so if it shoots out what will happen viscosity goes down. So if viscosity goes down dispersion will be a problem number one.

$$\dot{\varepsilon} = \frac{3U}{\sqrt{(2H_0R)}}\left[\frac{\alpha(1+\beta^2)(\delta^2-1)}{(1+\alpha^2)^2}\right]$$

Number two it can you know so shear rate will be reduced and second one each rubber has a particular stability thermal stability it can undergo I mean kind of a degradation which is not really I mean you do not want to have it and third thing while dealing with the crosslinking agent you know accelerator it can undergo scorching that means premature vulcanization so that you do not want. So you need a very efficient heat transfer system and in the other hand when you try to deal with the initial phase when you try to form a band particularly for synthetic rubber, mineral rubber like silicon rubber it does not form band at an ambient temperature so you have to heat it up so you need to have a heating and cooling system. So in a laboratory rolll you have a centrally cored place where you have a sprinkler you have a I mean fluid flow but if you have a big commercial or in a industrial roll I mean you cannot afford to have a centrally cored one and cooling everywhere cooling remember it happens in the surface so it is called peripherally drilled one it is typically 25 to 50 millimeter down the surface of it you have a cooling channel coolant channels actually so that is how it functions. So you understand here centrally drilled and peripherally drilled one. One for the you know smaller ones in the laboratory one and second one is by a large practice for the commercial roles basically where you mix 100 kgs of it 50 kgs of the sample in per batch.

While in the laboratory one we are talking of 1 kg or 1 and half kg or even less, even sometimes 100 grams down to 100 grams of rubber so requirement of cooling of the bulk rubber is different from one compared to the other that you have to keep it in. So for most general purpose rubbers maximum temperature you can foresee 130 degree in fact natural rubber you can start from room temperature onwards but rubber like as I mentioned synthetic rubber and mostly the silicon rubber and all mineral rubbers you have to do at a little higher temperature just the beginning of the mixing and then of course you have to have a cooling on otherwise it will overshoot. Well your sample can undergo degradation viscosity can be so reduced that your dispersion will be a problem. Remember one thing we are trying to put in shear force mechanical forces via the rubber matrix to the filler aggregate or to the ingredients. So if the rubber viscosity falls down it will be practically impossible for you to break the aggregates or agglomerates to have a good degree of dispersion which is one of the major goals in rubber mixing.

So that is one of the reason why actually even twin screw extruders even though it is a very efficient it can impart very high degree of shear forces but it is seldom used the reason is that cooling efficiency. In 2-roll you can have it with a peripheral drill machine on the contrary for a internal mixer you can achieve that by having efficient cooling system inside the rotor outside the jacket and even in the ram position also in the ram on tip of the ram you have a cooling system cooling fluid. So that efficiently takes away the viscous heat that is getting accumulated because internal mixer is even tricky because the rotation rpm when we are talking about a 2-roll mill is 10 or 15 rpm we are talking about. When I talk about internal mixer like Banbury we are talking about 50, 60 rpm and that too it has many nip actions in between the rotor two rotors and also in between the rotor wing and the chamber wall. So per unit rotation unit time you have heat dissipation much more so you need to have take away heat faster from the system.

So that's why you cannot afford to have the mixing the same rubber mixing done in a, for your information in an extruder twin screw extruder for your information even in a single screw extruder L by D ratio typically chosen for manufacturing pipes hoses are smaller. The reason is that if you happen to have a high L by D ratio the degradation chances will be much more so that is one of the primary reason why. So this is very interesting you can solve a very heat transfer problem one of the problem is given in B.R Gupta's book itself with data specific heat and every other parameters to calculate amount of heat transfers. So essentially if you consider this is the inside wire so wire from the heat is coming during milling because of the viscous system.

You consider a system temperature T and what are the means you can take away the heat by loss to the cooling fluid that is 90 percent of that the circulation system I talked about something which since it is a open mill it can be heat loss by convection to the air and radiation of course is very less nominal it means one or two percent maximum reason is that if you recall Stephan Boltzmann's law it is T^4 we are talking about a nominal temp which is so radiative heat transfer is minimal here anyway. So you can understand major cooling all depends 90 percent of it depends on the convective mechanism like where you are putting your coolant. Normally a tampered water is used not the chilled water in order to maintain the consistency from summer to winter otherwise it will vary the rate of cooling. So you have to again change that flow rate etc in the pump. So those who are interested in heat transfer that is also very interested area and particularly so if you try to make a machine and then try to make a really commercially large machine.

So initially we make a small machine with this all consideration I showed you very briefly about the rheological parts what is the strain range shear rate range that first of all you design and then you try to work on the heat transfer system of it and then make a small machine and then try to have a larger machine there are various means by which you can scale up that is typically called scaling up concepts in engineering basically. So that is what and what in a 2-roll mill operator does every time cuts it folds it in order to additional homogeneity of this distributed mixing. So that is manually done although today's 2-roll mill machines are fitted with many ancillary equipment's that helps you to automatic cutting and stock blender is action taking it from one end putting it to the other end of the roller some deflection rollers are also used by the time. Otherwise it is a fully you know manual driven the operator has to be in the front cut it from the one edge put it in the other edge and also sometimes take out the seat make it a pig roll like egg roll and put it at the central part of its in order to all this thing you do to make sure that it homogenizes and remember one thing this is very important a operator has a skill to maintain when you with the lead screw we can open the gap between the roll. So you slow open that one thing is widely wide open and the thing gets narrow closed system then you will be you know distribution of shear stresses very heavily.

So in that case putting make sure your materials spends equal time both are the you know wider separation and narrow separation then only you can make it homogeneous. So that is why cutting and folding action is very necessary. Maybe I am too fast but nonetheless my intention was to just to make you familiar with the unit process unless you practice it just try to see the demonstration how it is being done and you can get it elsewhere also videos and those who are from industries they themselves practice it every day so it is nothing new story for them so I am trying to go little faster at least at this stage to depict you the process operation. So different parameters as I mentioned two important parameters in the whole whatever I told you so far one is the rheological properties I mean both the filled and gums systems other day I was talking about so that means viscous and elastic part as I mentioned it you have from the basic rheology you can actually figure it out how much it is elastic how much is the viscous and that actually if you remember I talked about 1, 2, 3, 4 regions it decided by which is the dominant actually region 1 is and region 2 is dominated by elastic events. So elasticity dominate you happen to have a you know elastic band form on a roll if viscous dominant it goes to region 3 and 4 your intention not either not region 1 not 3 and 4 you have to confine and finish your operation within the region 2 itself so that elasticity versus viscosity balance matters a lot to have a good processability.

Good processability means you make sure it stays within the mixing time within the region 2 that is what I mean and at the end I get good dispersion and distribution. And second important parameter is the failure that means elongation at break as I mentioned it to otherwise there will be tearing pattern in the band and it will be devoid of good distribution in dispersion at the end. So most influential factors it depends so these two parameters important as I mentioned and what are all properties it depends molecular properties as I mentioned other day physical characteristics of the filler interaction between the filler and rubber And then finally temperature and mill parameter you call mill kinematics like I said roll geometry like roll diameter, nip gap as well the rolls free and friction ratio. So these are the primary parameter on which it depends. See as I already mentioned it to you at the beginning that you have two types of molecular weight one is number average another is weight average rheologically weight average is more significant than the number average.

Number average remember it actually dictates the colligative properties. Weight average dictated by you know the rheological properties of flow why? See rheology is related to flow so flow means larger molecule if you have more number of larger molecule there will be sluggish and the rate determining step will be flow of the sluggish molecule. So is the reason why weight average molecular weight is very close to rheological property although the viscosity average molecular weight comes in between the Mn and Mw. But it has more bias towards the weight average side of course. So as I mentioned other day if you recall three important parameters it comes.

One is zero shear viscosity reason why? Because ultimately your dispersion depends on the viscosity of the matrix. So higher the zero shear viscosity higher will be viscosity easier for you to. Second thing is the maximum relaxation time it is abbreviated by tau max sometimes. What is tau max actually? If you have a master curve with the time of course not temperature I am switching from time to temperature. So you can see this time when it starts flows it is called maximum relaxation temperature and which is correlated with Mw bar rather than Mn bar.

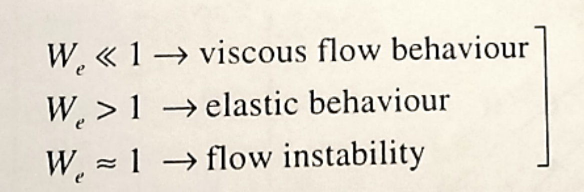
And other parameter already I talked about which is actually called you know elongation at break. So these are all very common things there is a critical molecular weight after that when I am dealing rather obviously the exponent of the it is 3.4 rather than 1. So for the highly entangled molecules. Elastic nature again it depends on the molecular weight if you have a higher molecular weight its elastic nature is more.

So elastic nature more means zero shear viscosity is more that means eta 0 is more tau max is more and lambda b is also more lambda b elongation at break. So all these three parameters actually favors the mill processability. Failure characteristics again if it becomes cheesy if it fails while it passes to the nip that is no good. Those are elaborated I wrote lot of things this will be supplied to you as a study material so for the timing I am skipping those. Molecular distribution I already talked about if you have a more molecular weight distribution lambda b increases but slightly so because your eta 0 may decrease.

So that is how is the reflection over all these three important parameter again to recall tau max eta 0 and lambda b. So how it is influential that it depends you please read through everything is very written very clearly and sometimes you intentionally add gel in order to increase the tau max and eta 0. That you favor you forming band in the region stay in the region 2 as well as zero shear viscosity for dispersion. So I am not going to elaborate each and everything but at the end you must understand one thing. So there is one thing called Weisenberg number what is Weisenberg number actually a particular system rather as a relaxation time say theta but when a rotates see if you have a H is the nip gap so $2H_0$ by 2 pi R N R is the radius of the roll and N is the rpm.

$$W_e = \frac{\pi R N \theta}{H_0}$$

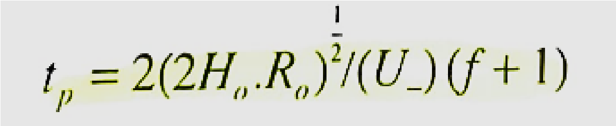
So that is the ratio actually gives you know your system relaxation time vice versa machine relaxation time. So if Weisenberg number is very very less than 1 it is a viscous part so it is automatic tendency to go through the region 3 and 4 and if it is you know greater than 1 then only elastic. So you have to so adjust with this mill kinematic parameter so that it stays in the region 2 that is how you decide better mill processability. So again if you see the free body diagram the picture of it see there are


$$\left.\begin{array}{l} W_e \ll 1 \rightarrow \text{viscous flow behaviour} \\ W_e > 1 \rightarrow \text{elastic behaviour} \\ W_e \approx 1 \rightarrow \text{flow instability} \end{array}\right]$$

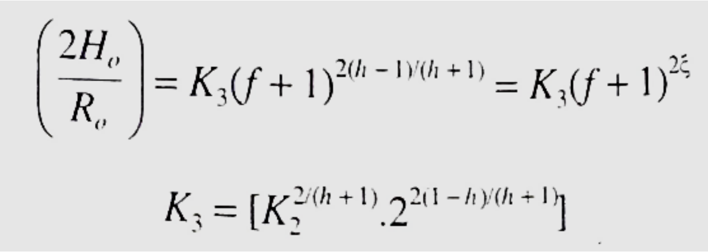
two force balance basically essentially.

One is the elastic force another adhesive force. So remember one thing think about this rubber is coming out if the u minus is a slow roll so this point these two points are in the same position but this point traverses this much by the time this traverses here so elastic tension develops. Now think about if the adhesion force tries to anchor it to the roll surface but if elastic force dominates it will try to take it out and it will snap back to the slower roll. So accordingly either it will go to the front roll and back roll that phenomena is guided by the balance between at least these two forces I am not considering gravity into account here. So this is a some kind of a dimensional analysis people try to do it in terms of you know critical nip gap process time means how much time it really spends in that nip area and with that dimensional analysis it is you can easily this is the dimensional analysis being done left and right. and Critical nip gap depends on this many parameters and then try doing your dimensional analysis from the dimensional analysis you set up your own equation over which this is very important I am not going into the details this is the t□ this parameter is important this parameter determines ultimately; I am not going into the details you can calculate out calculate out further calculate out from the further analysis those equations those.

$$\mathbf{2}H_0 = f_1(t_p, \mathbf{U\_}, F_a, \eta, \mathbf{P}, R_0)$$

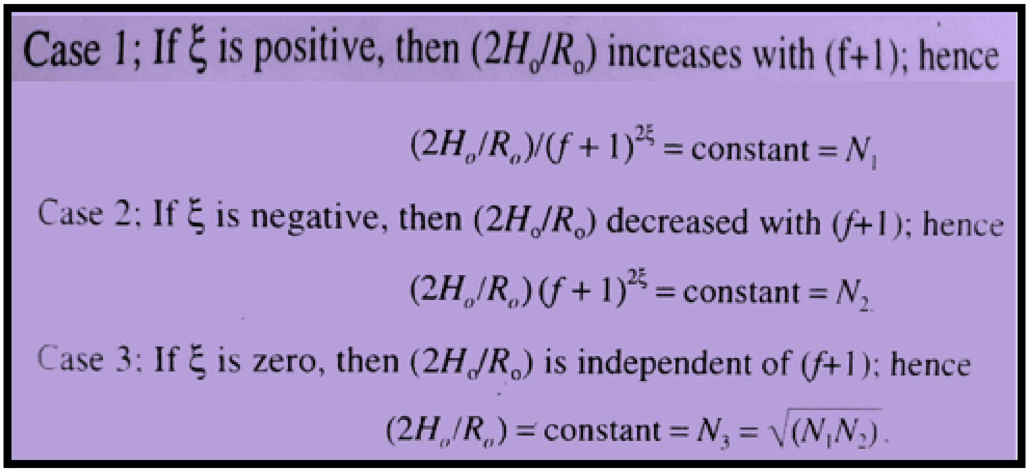

$$t_p = 2(2H_o.R_o)^{\frac{1}{2}}/(U\_)(f+1)$$

So, remember two things two forces I am talking about those are actually influential one in one hand you have a adhesive force other hand the elastic force. So if the adhesive force is high in nature it will go with the faster roll if elastic force is dominant it will try to take it out from the faster roll and snap it back on the slower roll. So normally you have a polar rubber as a tendency always to go to the back roll because adhesion force with the roll may be higher. So that is the factor and this is how if you take the moment of adhesive force of moment of elastic force that ultimately boils down here all those parameters I did not elaborate you and that ultimately essentially says how the front to back transitions slow roll to fast roll how it will undergo transition basically. I am going too fast I understand but try to try to follow up everything everything will be shared but bottom line is that book of B.R. G. Professor B. R. Gupta you try to follow it up these are the some of the things and what we are trying to do ultimately come up with the other kinematic factor which is mill kinematic factor which is friction ratio F. So classically you try to figure out made it band exponent basically. So whether it is positive or negative depending on you can really predict that with the friction ratio whether it will go to the front roll or it will go to the back roll vice versa. So making sure some constants is different say for example this is a constant. So, in this case if you really increase the friction ratio then R is not change it is a radius of the roll only thing which can change the critical nip here.



$$\left(\frac{2H_o}{R_o}\right) = K_3(f+1)^{2(h-1)/(h+1)} = K_3(f+1)^{2\xi}$$

$$K_3 = [K_2^{2/(h+1)} . 2^{2(1-h)/(h+1)}]$$



Case 1; If ξ is positive, then $(2H_o/R_o)$ increases with (f+1); hence

$$(2H_o/R_o)/(f+1)^{2\xi} = \text{constant} = N_1$$

Case 2; If ξ is negative, then $(2H_o/R_o)$ decreased with $(f+1)$; hence

$$(2H_o/R_o)(f+1)^{2\xi} = \text{constant} = N_2$$

Case 3; If ξ is zero, then $(2H_o/R_o)$ is independent of $(f+1)$; hence

$$(2H_o/R_o) = \text{constant} = N_3 = \sqrt{(N_1 N_2)}.$$

So essentially what is the influence and this Xi is actually related to the polar to non-polar one case for the polar rubber it is I think it is a positive number and for the non-polar it is a negative number. So accordingly you can decide your Mill band constant basically or exponents. So that determines where it goes. So, I was really too fast to cover it up but nonetheless I try to split it you can understand why I put it in two parts but I do not have any scope within this course but if you have any difficulties reading Professor B. R. G's book, we will have a discussion session in that I will clarify this is a book again I will re-emphasize a purely taken from that book. So some of the constitutive equation everything I really just give any way bird's eye view only not really went into the depth of it. So as is whatever I covered so far to give you a basic understanding about the rheological phenomena it happens to give you some clue some sort of a tool to control yourself I mean control the rubber restrain the rubber in region to specifically I mean ultimate goal is to having very good dispersion and distribution and to resist the switch from one region to other to resist the switch from you know front to back roll because you always want it to be in the front roll. So that is what it is all about two roll mill I will not cover it further but hope it has given you a very basic understanding from my lecture which was really first I know that but one thing you must know whatever I talked about 2-roll processing there is a mother of all mixers there is the first thing people have done it internal mixer is nothing but it is a more making more mechanized more controlled way although geometrically it is different one case you have a cylindrical roll so other case you have a inside a cavity rotor but mechanistically it is all the same. If you add up you know shearing action add up the manual handling cutting back and forth putting it making it roll everything automatically happens in internal mixer.

So let us see in the next lecture how we do it in internal mixer. Thank you.