Rheology and Processing of Paints, Plastic and Elastomer based Composites
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Lecture 40

Rheology of Injection moulding process

Welcome to NPTEL online certification courses on Rheology and Processing of Paints, Plastic and Elastomer Based Composites. Today, we are on week 7 and its lecture number 7.4. It is all about Rheology of Injection Moulding Processes. In fact, what I we are going to learn today is the basics of injection moulding. As such injection moulding as I told you already is a bit complicated process.

Part of it is extrusion, part of it has a flow and part of it after flown, it is a pressure rise you know shaping operation. So, it is a combination of those. So, concept covered would be injection moulding cycle. What I mean by cycle like I last time told you.

So, this is a typical injection happening and there will be some zieth in which different made moulds will be situated and one in one go will come and get attached to that part of it, two part of it and then gets injected. And each in between you know injection part there are you know spure you know runner as well as gate that ultimately fills the molten polymer into the cavities. So, some of the this cycle a complete cycle I mean from the conveying to injection to the mould release as you can see from this cartoon. It is injected, it is mould filled and this final product is made that completes one cycle basically. So, process description little bit on the flow and injection actually when it is done when it fills the cavity very high as high as 1300 you know bar of pressure is involved ok.

So, pressure has certain roles there and it ultimately has certain roles the cooling and pressure that means, temperature and pressure balance on top of the flow type of flow you may have a frozen in orientation I talked about other day residual stress component of it and those are to be taken into account to have a perfected you know injection moulded things. And what are all the effects on the output I mean in terms of the cylinder, inside the barrel what is the temperature, what is the density, how does density if I have two polymers equal MFI we vary the density how the output affects ok. And bit on reaction injection moulding, but I mean I I mean whether however, the reaction injection moulding is bit different from traditional injection moulding process which is the heart of injection process, but nevertheless reaction injection process is also kind of injection and a wide gamut of products are actually made by reaction injection I thought that covering towards the end ok. But one more important thing I will point out for rubber especially for the mounts and rubber to metal mounted other products also bushing, bearings, okay, injection moulding is a preferred one. So, I am not taking into that complication I am assuming inside the mould only raw rubber is, you know placed in I mean I am not talking about the insert or metal of certain geometry are whether there and along with that you have to make the quite integrated mould or not it's a simple polymer going inside the mould that is the story I am going to talk about ok.

So, without going into the complication for a beginner. So, keywords once again residual stress is one of the important keywords and rest of the things I already elaborated, but shrinkage and warpage is very important these two terminologies for you know injection moulding process particularly of course, it is relevant to all sorts of a moulding processes plastic moulding processes, but from this point of view it is very important. So, now let us try to first understand the process. So, injection moulding cycle as I mentioned it to you the sequence of operation that one has to do I mean and that you are doing over and over making the process a batch to a continuous process ultimately. So, two halves of the moulds are closed by clamping unit I talked about that clamping pressure also plays very important role how you clamp them together and at this point the mould is empty and a sort of you know melt is ready inside the barrel that time already I assume that you conveyed it there and that has to be injected slide inside the you know injection mould.

So, the very first process as you can see the clamping of the mould first putting it in place. So, with the you know injection nozzle it is fit in basically this part of the sprue as well as nozzle part of it in fit, and a moulds are in place two halves of the moulds are closed. So, then the injection of the melt occurs when the screw acts as a plunger and the melt through the nozzles screw and runners into the cavity as I mentioned it to you and during this time the non return valve remains open, the non return valve will be closed once it is fully injected. So, injection pressure usually at a reduced level hold on pressure is maintained till the gate are freezed, to counter the shrinkage of the melt during the cooling. So, that is what this is the first part.

The second part the non return valve closes it will not allow to return back the I mean melts which are already inserted inside the cavity of the mould. So, and the screw rotation starts it is actually the pressure is developed at the valve and the screw is pushed backward while still rotating to accumulate the next slot it is getting ready for the actual next slot. The third thing during the above period the melt inside the cavity continues to cool. So, cooling starts you already filled it out and when it has reached the ejection temperature, the mould halves open and I will show you with one numerical problem in the upcoming classes how to calculate what pressure you should actually open, what temperature you should open when the pressure actually goes to atmospheric pressure how do you do balance that with certain, you know isotherm the thermodynamic isotherm I will show you. So, this is part of it and then this is the fourth one the mould closes and cycle is repeated.

So, essentially 1, 2, 3, 4 that completes the whole cycle you can see from here. So, that is what I mean by a whole complete injection cycle. So, let us try to see it from the fluid point of view. Molten thermoplastic exhibits viscoelastic behaviour as I mentioned it use several times throughout the course. However, when you have a thermoplastic melts its elastic component is little less than that of, you know rubber elastomer, soften elastomer why? The reason is the molecular weight, molecular weight is much higher for elastomer and therefore, entanglement, you know entropy part plays important role whether to you know align it or it will snap back.

So, that's what the elasticity it comes entropy driven elasticity I already talked about at the very beginning of that. So, this actually which combines the flow of both viscous liquid and elastic solids. So, it's a typical pattern that's what from the very beginning I was trying to make you very clear. So, when this viscous liquid flows the energy that causes the deformation is dissipated and it becomes viscous heat. So, that is how the each cycle the hysteresis small small hysteresis loops are created and that will manifest in the form of transformation of mechanical energy to thermal energy that's what it happens exactly.

And on the other end when the elastic solid is deformed the driving energy is stored. So, that is how you can anticipate how viscoelastic material gives rise to heat upon deformation. So, in addition to this I mean this you can anticipate there are two types of you know stresses, one is like a shear stress that you can see it from here I already elaborated with the flow curves and all I am not going into that again. And another one happens there will be some certain sort of a elongation. So, both elongational flow as well as shear flow will be omnipresent inside there in the whole course that I depicted so far.

And on top of that you know the what type of a deformation you anticipate one can be simple shear, another is a simple elongation that is what it is manifested. So, see from this figure if you have a simple shear then you can see the velocity lines velocity profiles of that moving forward. While see this carton shows your how it is getting elongated this is the total volume and this gets elongated basically and that is how it passes us. If you consider a small little volume element there that is how the you anticipate the deformation. So, the flow of a molten thermoplastic during injection molding filling is predominantly shear flow.

However, the layers of the material slide each other that is what the shear is. However, the elongational extensional flow becomes significant as the material elements undergo elongation when the melt passes through abrupt dimensional sets. Suppose if you try to see the some of the you know you have a flat mold and with that we have some contours some intricate sort of a design you have in the final molding. So, in that's getting elongated while flowing suddenly flowing through a when open channel to close channel smaller channel basically and that is where your elongational viscosity also plays very important role. So, if you do not go into the complication if you just take a simple flow it will be obviously nominated by shear forces.

Another gross simplification we always make we try to make during the whole process upon the change of pressure, upon the change of shearing change of you know different channels, we consider viscosity remains unaltered constant property of the fluid in many of the gross designs we do, but actually is it so? No because so far what you learned it this is not true for a complex materials any polymer you consider or particularly dispersion it is even more complicated. Polymer having some dispersed particulates it can be in the plastic it can be in the rubber, it can be even in a fluid. So, considering those in such cases the viscosity of the material either decreases with the rate of shear, that's what you learned the shear thinning time pseudoplastic or it can be dilatant it can increase that is what is depicted for your recap although it has been elaborated at length. So, when the polymers is deformed there will be some disentanglement and slippage of the chains over each other and molecular alignment in the direction of the flow is bound to happen basically. And as a result the resistance exhibited by the polymer to flow decreases with the deformation and due to the evolution of the microstructure, in which tends to align into the flow inside in the flow direction direction of the flow.

And in addition the melt viscosity also depends on the pressure and the higher the pressure the more viscous the melt becomes as obvious. So, pressure has also low role this figure actually shows you depiction. Suppose if I have log viscosity versus log shear rate that kind of a pseudo plastic behaviour. If you increase the temperature this curves tries to tends to go down that means viscosity goes down. If you apply more and more pressure see which tends to go up.

So, that is the opposing effect happens between two parameters temperature and pressure that you have to keep in mind while designing that. So, the shear rate distribution also plays very very important role. The faster the adjacent material elements move over each other higher is the shear rate that's how you define actually velocity gradient dv dr that is what you define as a shear rate. The shear rate is highest at the mould and melt interface when it is just entering and it is making the interface there. And on the other hand the shear rate approaches 0 at the central position.

So, that is how you have to consider because there is no relative material element movement due to the flow symmetry. And shear rate distribution in injection mould filling you can see it from here where is the maximum where is the minimum that you can anticipate say shear rate is maximum somewhere here and minimum somewhere in the central location. Let us try to understand the manifestation variation of the pressure. See try to understand the entire cycle of it and as if the fluid is flowing through the sprue followed by the runner and then goes into the gate and through the gate it actually goes in inside the cavity and finally, it should be released.

So, pressure drops. So, initially in the sprue position is a entrance pressure as you can anticipate pressure is high, but over time it is dropping down and under the full transition from the entrance to the sprue end. So, then through the runner it goes and it is reduces, but not reduce at that drastically. And then finally, through the gate you see is a drastic reduction and final reduction and finally, once your moulding cycle is over it approaches the atmospheric pressure and at that point of time you are ready to open the mould basically that I will show you the numerical problem. So, step by step point by point what it's pressure is driving force that becomes the resistance of the polymer made to fill and pack the mould cavity. As I mentioned pressure means again the viscosity part of it.

So, pressure molding phase process essentially involves four phases filling pressure switch over point I will show you one by one pressure phase cooling phase this four you consider from this graph. So, let us try to see volume and temperature relationship from there. So, you can see here initially at the entrance just prior to entrance you have a one bar pressure say. So, that pressure in certain transitions switch over point it goes to point B where it is 200 bar. And finally, eventually reaches a point where 90 percent of the materials are filled in, that means you have a pressure say 600 bar here.

Now what if after that what it happens there can be sudden transition to D say, why your rest part of the unfilled portion will be filled out and what you can see from here at this stage the volume remains constant essentially volume does not change and this particular phase is called pressure phase. So, you can understand here the filling phase starts from here and this is a switch over point and then you have a pressure phase and then finally, here to here you cool it down and pressure finally, dissipates basically. So, that's how you can look it from the conception point of view how injection molding total cycle works. Clear? So, again I will repeat some of the stuff, but we will try to see some of the artefacts some of the concerns you have to make while dealing with the injection molding. High speed filling phase is changed to the pressure phase at the switch over point.

Clear? Like I elaborated and during the pressure phase the speed of filling is less. As I mentioned 80-90 percent is already filled out with 600 bar something I will show you right. So, material which is already injected into the mold expand and fills up the entire cavity the rest of which it will exclude wherever the empty spaces are there and since the mold walls are cooled or cooled the specific volume of the melt decreases that's another concern.

So, mold wall is cooler than that when it is injected. So, there you have a frozen in orientation that component I elaborated last time that events will take over a prominent role and at this point to compensate of the shrinkage more mold is injected at low speed.

So, this is another constraint. So, frozen in orientation let us look into that from this figure. Development of residual force stresses due to frozen in orientation during the filling and packing stages. One high cooling shear and orientation zone and low cooling zone. So, here you can see the that with the temperature and with the shear stress and you see the combination of it you see the orientation the later part here which is actually in the cooling part of it in immediate vicinity of the wall and you see that the concerns you have to take it. One is because of the shear force shear flow another concern is the temperature here and you can see here it shows the position of the screw during each stage of it starting from the, you know feed zone feeding to the accumulation zone where you have a cushion and then you fill it in and that is how your movement happens basically of the fluid.

The process condition that reduce the shear stress in the melt will reduce the level of flow induced residual stresses. Residual stress is important because you are stressing it you do not have much time to relax so that can be relaxed if you increase the temperature relaxation will be faster. For any relaxation process higher the temperature relaxation will be faster that's what high melt temperature high mold wall temperature then no question of frozen in that component of it. Shorter flow path if you have a shorter flow path less memory will be there for the polymer after deformation. And then longer fill time but that is not that is in the contrary of the productivity actually and decreased packing pressure.

So these are the components which can take care of flow induced residual stresses that will appear ultimately as a artifact or defects or imperfected molding basically you get ultimately by injection molding process. And due to combination of high shear stresses and high cooling rate adjacent to the mold these are the two things as I mentioned one is temperature another from the shear stress and there is a high oriented layer frozen immediately below the part surface. See that actually becomes a thermal insulator layer and as a result temperature anyway is coming from the wall part of it cooling temperature so it takes time. So essentially while the part in the immediate contact of the wall is solidifies and that inside there it will be still in the liquid phase that is the complication it happens. So this thing also is very important subsequent exposure of a part with a high residual flow stress or flow frozen in orientation two components to high temperature may allow some of the stresses to relieve.

So that's why I told higher temperature is a solution there and the typical results in the what it happens, these two component gives either shrinkage, shrinkage will solve a numerical problem taking into consideration, compression molding will not take into consideration injection at this part because it is a beginner level course and also you know warpage deformities that happen. And due to the thermal insulating effects of the frozen layer that I pointed out here the polymer melts in the hot in the core able to relax to a higher degree leading to a low molecular orientation zone. So let us try to see another effect because of this frozen in layers and this effect is you see in the literature called fountain effects. And the phenomena how do you define it causes the flow of the, you know deviating from the two dimensional flow between the parallel plate I mean you remember a parabolic flow I showed you and that deviates and it terms of fountain what is the fountain you see the deviation happens I mean it is not exactly parabolic flow line that we derive for a flow through a cylinder you remember. And it actually ultimately develops and your frozen in layer is not very continuous here and here it has a fountain flow back flow here.

So that's also one of the concern it's noted that melt does not reach the wall by sample forward advancement but rather tends to flow down the center of the cavity of the melt front and then flows out toward the wall and it can have a significant effect on direction of the flow induced orientation of the polymer molecule and thus on the microstructure of the finished product. Finally microstructure think about the property what you get it in this wall is going to grossly going to different what you are going to achieve afterwards. So that's what so mold shrinkage again is a very important or intricate part of it any mold you design. So we will try to solve a elementary problem we will not go into the whole design of it. But let us try to understand thermally induced residual stress due to the following reason why it happens material shrinks as the temperature drops from the process setting to a condition when the ambient process is completed.

And the material elements experience a different cooling rates and packing thermal mechanical histories as the material solidifies from the mold wall to the center. You see there is differential solidification rate and changing pressure and temperature and molecular and fiber orientation results in variable density and mechanical value. Now think about if a polymer is a semi-crystalline one the process is going to be even further complicated as compared to if you consider a amorphous polymer like polystyrene say correct. So certain more constants prevents the path from the shrinkage in the planar direction think about this is the molten polymer in the early stage of cooling. And then what happens since you have a differential temperature as a result this envelope will form and this envelope is going to show you some sort of a shrinkage part of it.

And not only that you see thermally induced residual stress those stress marks can even appear basically, inside the finished products that you know like nobody is going to buy your product if you end up having this sort of a deformatives particularly on the surface it loses its surface gloss. So these are some of the consideration that one must understand deeply about the process. Then again I will elaborate that frozen in orientation what it is happen if it is uniform fine, still you can afford to see like in the figure C that is usually happens. But it may end up having the worst case like B.

So that is what I want to mean here. So during the cooling stage let me read it when the external surface layer cool and start seeing the bulk polymers at the hot core is still molten and free to contract basically. So whatever it happens on the wall it is happened but it is again it will try to contract the immediate next layer and next layer that way you can consider the entire you know moldings into different sub layers basically and that they have a differential shrinkage. So residual stress is a process induced stress frozen in a molded part it can be either flow induced or thermally induced as I mentioned already again it is a repetition and residual stresses affects the parts similarity to a externally applied stress. And if they are strong enough to overcome the structural integrity of the part the part will warp upon ejection which will bend actually. So entire you know motto is gone defeated and then layer will make crack also.

So that is the you know downside of it or extreme cases it may happen. So as I mentioned in case of B the intermediate layers tends to shrink less than the others because of the lower frozen in specific volume. And in reality all layers are bound together and therefore, the end result will be a compromised shrinkage distribution with the intermediate layers being compressed outer layer which being stretched. So that is what will be the manifestation you can understand from here.

I am not going into that. So you have a one stage if you have a residual shrinkage it depends it will be you know tension and intermediate next to the layer will be compressed. So if it is a symmetric still tension compression you have a symmetric structure like I showed you I mean at least you can get to see this kind of a structure. But it can go worst with the residual stress distribution and you can have a very asymmetric where compression dominates tension is less. So similar so thermally induced shrinkage is very vital and it can shrink but without the wrap. But when it is flow induced as well and thermally induced you can see it will shrink as well as it will wrap.

Just schematically trying to show a particular you know arbitrary volume element how it appears. So anyway I mean this is what for your visualization sake nothing rather than I was trying to repeat the same thing what I told you. Now what is important the output rate of the molding. First of all you know you are molding it you have to consider the first part of it that means when it is trying to fill the cavity. So a typical curve you can see volumetric output versus cylinder temperature.

And what is important initially the entire process again I will give you a recap. It is pushing cylinder is pushing I mean ramp is pushing try to take it in that reservoir position and then trying to inject it. Injection is over second unit process third unit process is a cooling inside the mold. So initially the rate will be limited by the this moment forward moment of it. So let me read it out then the process will be clear to you.

As the temperature increases the output also increases. The reason for this is that at low temperature a long cycle is necessary to melt the granules thoroughly. But as the temperature increases the melting time becomes shorter and therefore the cycle is also shorter. So that with the increase in temperature you see the output rate increases. But at certain point what will happen is reached soon when the time taken to melt the granules is no longer time limiting rather the other component third component of it will take over. The greater parameter of importance then is the time taken for the moldings to cool it down to a temperature and for the release extracting it.

So is the two side of it is depicted graphically hope it makes sense to you. Then again it depends on the density. See as I mentioned it you two polymer may have same MFI but density is different. So if I ask you the question which case output rate will be faster given a similar mold design I mean starting from the you know ramp to the you know all the cavities and everything remains same. So if it is the case it indicates from here you can see clearly, that higher the density higher the output rate on the cooling side of the curve at a given cylinder temperature.

And you can see here higher density materials however requires higher cylinder temperature to produce the adequate melting of the granules that is also the downside of it that way. So you can see in this thing moldability scale you can put it 0 to 10 different-different, you know engineering plastic and commodity plastics at different temperature ranges. So that you can realize this charts are actually available for polycarbonate you are suppose you try to pick it what's the typical temperature range and where you have a better moldability of the material. So without going into the details let us I hope you have understood the entire process of you know injection molding and its complication but let us try to touch upon the reaction injection molding. So the process begins with two component isocyanate and polyol, which are stored in a separate large tank, tank 1, tank 2, 1 for isocyanate another is polyol and then you have a flow line of it.

And of course you have those as I mentioned it to you in injection molding also you have a non-return valves when it pushes in it fills it then non-return valves closes it closes and open and similar so there should be a pump and flow lines here in wall. So there finally you see it's a same to same similar to that the flow stream is getting injected two components are getting mixed intermingle and they are getting injected inside somewhat heated mold and then it gets cured and then getting coming out. The process is simple but it makes your life easier because you are flowing them in the liquid form already. So it does not have those of viscous consequences that I talked about like say elastic memory say in the form of you know all the other consideration at high temperature operation stagnation frozen in orientation residual stress those are much less.

So your surface finish will be much much better. A piston that retracts inside the mix head and breaking the loop and allowing the two liquids to combine. So there is a intermim mixing part of it. The liquids are mixed at a very high velocity using an impinging mixture before that transfer into the mold. So that is the reservoir part. There we are not considering we have to mix it here but in addition here the one mixing component is also important.

And rim provides further memory saving benefit via the light weight you know machined aluminum molds. And mixed polymer cures inside the mold using a combination of low pressure. So approximately 100 PSI and heating of the mold around 180 degree centigrade Fahrenheit of course and that is closely about 80 to 80 Celsius and cure time within the mold vary from several minutes and depending on the parts of the geometry its complication intricacies etcetera etcetera and wall thickness. So these are the some of the products I just highlight that is also another part of the processing that is why I wanted to highlight here. Foam solid foams fiber reinforced things even the composites you can reaction injection mold like the boxes or others.

So polymers and rim processes can be chosen to produce solid elastomeric rigid foams flexible foam finished products, continuous long products also you will be able to make. Remember what I before I wind up these are the some of the references I already talked about I have given you what are all book you must read. But most importantly what I did not talk about was I mean metal to rubber bonded product, metal to plastic bonded products that complication but I try to elaborate or emphasize upon the basic processes involves and some of the concerns some of the parameters that you have to take care in the design but although in this purview of the course, we do not have the design of injection molding machine its outside the purview of this course. So later on we'll see if we can coin it based on your request your things we may do it, as a computerized computational mold design as add on later on it all depends on over 2-3 years, what is your sort of a interest that will stimulate us to go forward. Again I am not going to give a proper conclusion but nonetheless entire injection molding process was elaborated.

And next time two important part in lecture 7 I will try to touch upon plastic and fiber related processing just in a bird's eye view I will like to touch upon and few of the numerical problems we will try to solve related to processing. Like earlier we have solved some problems numerical problems related to rheology and now we are going to particularly the mold shrinkage, particularly about the extrusion volumetric flow calculation and let me see something on the two-roll processing or something may be on the calendaring if time permits with that thank you very much.