Chapter

Chapter Review on Computer Simulation of Melt Spinning: A System of Systems Perspective

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Abstract

This chapter discusses an approach for process simulation in the design of melt spinning process for finding optimal design parameters concerning spinneret, quench air unit and other technical parameters for maximum throughput and quality. The property of as-spun fiber is a function of structural parameters at a given condition and orientation of the structural parameter and it is highly governed by stress level at freeze line. Thus, to define structural property and associated relationship, it requires to identify the process to control the variables (or factors) that affect the structural parameter as well as final fiber property. In addition, this chapter also provides a System-of-Systems (SOS) perspective on melt spinning process and its computer modeling along with mathematical equations for estimating spinline stress with a change in process variables. The spinline stress will be used as an input for a computer simulation to have process optimization by changing the necessary variables until it optimized.

Keywords: melt spinning, system-of-systems, poly ethylene terephthalate, simulation, process parameters, process optimization

1. Introduction

Modeling and Simulation (M&S) have become important tools for evaluating and scheming a melt spinning in a comprehensive arrangement of disciplines fluctuating from fiber spinning and engineering to melt spinning [1]. For example, in engineering scheme, modeling the parameters and simulation used to evaluate the effectiveness of a melt spinning process concept, verify whether all the functional design specifications are meet, or suggest modifications for improving the manufacturability of a product [2]. Melt spinning processes are considered as a system-of-systems process based on the thermoplastic polymer processing method as shown in **Figure 1** [4]. For this process a system is required to ensure the polymer is melted above its melting temperature, and the melted polymer is then transported to another system where it is metered for constant mass through a spinneret into a quench air stream blowing across the spinline [11]. The Spinline-and-Free-line" forming can be considered as another system that is used to form spinline, cool and finally solidify at a distance from the spinneret called 'freeze- line' [14]. The solidified polymer filament is winding at a speed significantly greater than the extrusion velocity; this cause the final cross-sectional area is considerably smaller

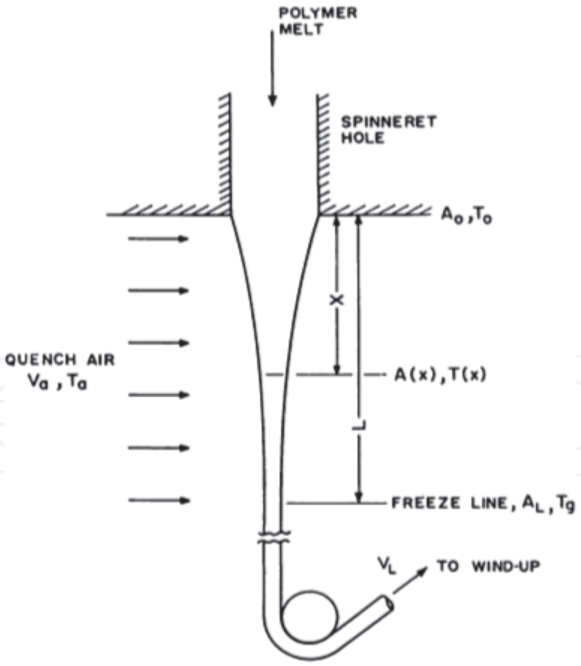

Figure 1.
The melt-spinning process.

(about 100–200 times) than the initial extruded area. This "Winding" process can be considered as another system in the melt spinning process [2, 21]. The way we decompose the melt spinning process into SOS view is based on the "System Control" view-point. For examples: (i) the melted polymer process is considered as a system because it requires a temperature control to ensure the polymer melts above its melting temperature, and (ii) the winding process is considered as another system because it requires to control the winding speed ensuring that the winding speed is significantly greater than the extrusion velocity [27]. Concerning "Spinline-and-Free-line" forming process, note that without considering crystallization in the spinline, solidified filament orientation can be represented by the orientation in the spinning threadline frozen at or near the glass transition temperature of the polymer due to result of tensile deformation under stress in the flowing melt. So, stress level at freeze line can easily govern the orientation, in which the process variables such as extrusion temperature, extrusion velocity, take-up speed, quench air velocity and temperature affect the stress level at freeze line. This shows that molecular orientation in the as-spun filaments is a function of extensional deformation and cooling. Cooling rate across may vary across the filament and cause a change in oriented filament cross section [19]. Thus, "Spinline-and-Freeze-line" system requires a complex system control to ensure accurate orientation, glass transition temperature, and tensile deformation under stress. In practice, the automation in melt spinning can be tested using simulation approach for estimating and gaining insight of the changes of process variables in order to reduce the risk on uniformity of the fiber quality [23].

2. Spinline orientation

Quantification of melt spinning requires the development of mathematical equations describing processing-structural-property correlations. The mathematical equations will be used in the computer simulation for predicting the fiber-line stress using readily measurable process variables such as melt temperature, take-up speed, and extrusion velocity and quantitative correlations between response variable like fiberline stress and structural parameter of the solidified fiber [14]. Using a simple quantitative expressions critical operating conditions and material properties for the melt-spinning for Polyethylene terephthalate (PET) identified. The method used depends on the experimental observation that for vitrified polymers like PET spun at speeds below 3000 m/min, the molecular orientation of the as-spun filament is uniquely determined by stress at freeze line when spinline stress is at the glass transition temperature [23, 26].

Clearly, the spinning stage represents a non-isothermal, uniaxial elongational flow situation with variable physical properties [14]. In order to develop the governing mathematical equations, the following assumptions will be used through this chapter.

1. The process is operating under steady state conditions.
2. The temperature and velocity field are independent of radial position.
3. The elongational viscosity is independent of extension rate and is equal to the Trouton viscosity.
4. All the molecular motions at temperatures less than the glass transition temperature, Tg.
5. The effects of inertia, gravity, surface tension and air drag are negligible.
6. Dieswell has insignificant effect.

Figure 1 shows the coordinate system used for the analysis. Based on the above assumptions, the governing equations can be written as:

$$\mathrm{W} = \rho \mathrm{AV} \tag{1}$$

$$\sigma = \mathrm{F}/\mathrm{A} = 3\eta_o dV/dx \tag{2}$$

or alternatively

$$\mathrm{dA}/\mathrm{dx} = -\rho FA/3W\eta o \tag{3a}$$

and

$$\mathrm{dT}/\mathrm{dx} = -2(\pi \mathrm{A})^{1/2}/\mathrm{WCp} * \mathrm{h}(\mathrm{T} - \mathrm{Ta}) \tag{3b}$$

The appropriate boundary conditions are

$$\mathrm{at}\,\mathrm{x} = 0, \mathrm{A} = \mathrm{Ao}, \mathrm{T} = \mathrm{To} \tag{4a}$$

$$\mathrm{at}\ \mathrm{x} = \mathrm{L}, \mathrm{A} = \mathrm{AL}, \mathrm{T} = \mathrm{Tg} \tag{4b}$$

Where L is the distance of the freeze line from the spinneret. The temperature, T (x), the velocity V(x), and the spin line tension F, are obtained by solving Eqs. (2), (3), and (4) subject to the conditions represented by Eqs. (5) and (6). In order to accomplish that, however, correlations for the temperature dependence of physical properties (ρ, Cp 'η_0) and the heat transfer coefficient, h, need to be provided.

Rheological measurements of the shear viscosity of PET indicate that it behaves like a Newtonian liquid for shear rates up to about 200 S^{-1}. Thus, the assumption of

Newtonian behavior may not be too inappropriate for PET [23–26]. The variations of zero shear viscosity of PET, η_0, as a function of intrinsic viscosity (IV) for different temperatures.

$$\eta_0 = 9.76 \times 10^{-3} (\mathrm{IV})^{5.2893} \exp\left[(6923.7)/(\mathrm{T} + 273)\right] \tag{5}$$

For density and specific heat, we assume the following linear variations with temperature [7].

$$\rho = 1.375 \times 10^{-3} - 0.75\mathrm{T} \tag{6a}$$

$$\mathrm{Cp} = 9.95 \times 10^{2} + 3.875\mathrm{T} \tag{6b}$$

For the heat transfer coefficient, the best available correlation is [23].

$$\mathrm{h} = 1.98\mathrm{A}^{-1/3}\left[(\mathrm{W}/\rho\mathrm{A})^2 + (8\mathrm{Va})^2\right]^{1/6} \tag{7}$$

A proper choice of F is crucial for smooth operation of the numerical procedure; a fairly good starting estimate can be obtained from the following equation.

$$F_{\mathrm{s}} = 10.635 \frac{\int_{A_0}^{A_L} h A^{-1/2} \mathrm{d}A}{\int_{T_0}^{T_{\mathrm{s}}} \frac{\rho C_{\mathrm{p}} \mathrm{d}T}{\eta_0 (T - T_{\mathrm{a}})}}, \tag{8}$$

At intermediate take-up speeds (3000 m/min), melt-spinning of PET results in almost amorphous as-spun fibers. That is why molecular orientation of the as-spun fiber is expected to represent the ‘frozen-in’ stress in the spinline [1–3]. Molecular orientation which is measured by birefringence quantitatively related to process variable form a link between the latter and the as-spun fiber properties.

Experimental data shown in **Figure 2**, for melt-spun PET fibers under different process conditions demonstrate that the birefringence is directly proportional to the spinline stress for PET,

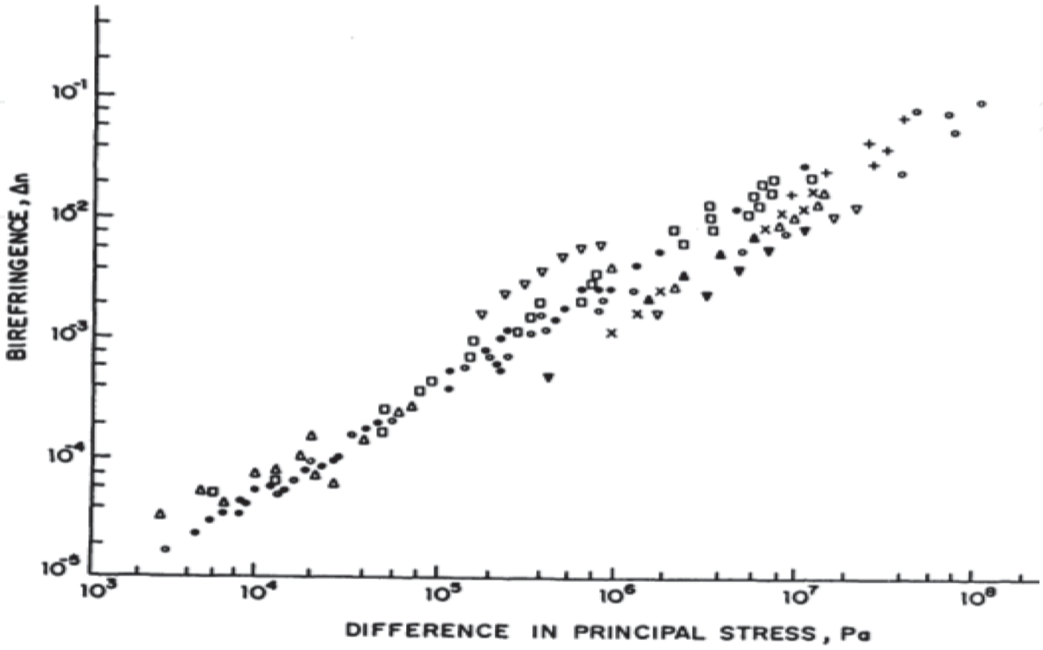

Figure 2.
Variation of birefringence with principal stress difference for PET with + = Mn ~ 24,000; ∇ = Mn on-line [3]; X = Mn 15,000; ○ = Mn, 17,000.

$$\Delta \mathrm{n} = \mathrm{C}\sigma = \mathrm{C}(\mathrm{F}/\mathrm{A}) \tag{9}$$

C being the stress optical coefficient [23]. The intermediate take-up speeds in a melt-spun PET fibers show amorphous at a slow crystallization behavior of PET, and the birefringence depends on the (experimentally measured) spinline stress. To show the relationship between as-spun fiber birefringence and the calculated stress at the freeze line, the stress at freeze line is taken to be the spinline stress at which the velocity is 95% of the take-up velocity [14, 17]. It is observed that a linear variation is obtained with stress optical coefficient approximately about 6×10^{-9} to 9×10^{-9} Pa $^{-1}$, which is then compared with the values obtained by different experiments [14]. For other experiments, the spinline stress controls the orientation of the as-spun fiber, which in turn determines the mechanical properties and associated fiberline processing ability. Thus, it is clear that stress at freeze-line controls the orientation of the as-spun fiber, and in turns it can determine the mechanical properties [7, 11]. The sensitivity of the as-spun fiber properties is directly related to the sensitivity of freeze-line stress to the changes in process variables. Stress at freeze-line, on the other hand, can readily be obtained from the process simulation calculations, provided the operating conditions and the melt properties are available [22].

3. Sensitivity analysis

Sensitivity analysis provides an approach to look into the effect of a factor affecting the response variables and making effective changes in the process parameters for controlling process stability and product quality improvement [1, 21]. As shown in **Table 1**, the critical process variables have a significant effect on stress level at the freeze-line are quantified for a typical PET spinning process [15]. The spinline stress is calculated under different operating conditions and melt properties, which is then used in the assessment of stress sensitivity, are shown in **Figures 3** and **4** below [23].

The results indicate that the changes in process variables like extrusion temperature, melt, take-up velocity and the melt throughput rate that can affect the response variables (e.g., stress at the freeze-line) [14, 19]. The slope of the curve provides a measure of the sensitivity of stress at the freeze-line to process variable

Process variable	Value
Intrinsic velocity	0.611 dl g^{-1}
Extrusion temperature	285°C
Glass transition temperature	67°C
Ambient air temperature	25°C
Quench air velocity	48 m min^{-1}
Spinneret hole diameter	0.00038 m
Take-up velocity	1500 m min^{-1}
Mass flow rate	0.001 kg min^{-1}
Spinline tension[a]	0.000972 N
Freeze line location from spinneret	0.37 m

[a] *Calculated value.*

Table 1.
Process variables for PET in a typical melt-spinning operation.

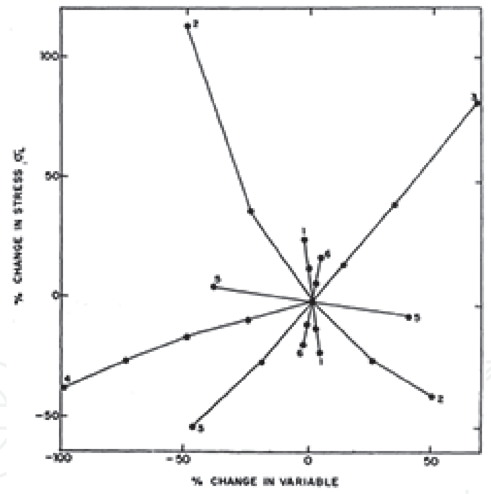

Figure 3.
Sensitivity plot for stress at the freeze-line. The various curves are for percentage changes in (1) extrusion temperature, (2) melt flow rate, (3) take-up velocity, (4) quench air velocity, (5) quench air temperature, and (6) melt intrinsic viscosity [14].

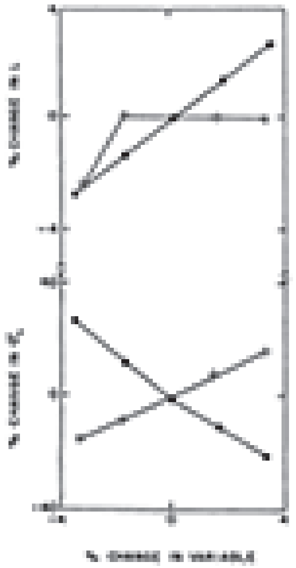

Figure 4.
Expanded sensitivity plot for extrusion temperature = ●, and intrinsic viscosity = ○ [23].

changes. In comparison, stress at the freeze-line is moderately sensitive to changes in quench air velocity and relatively insensitive to alterations in the quench air temperature [23]. But it is more sensitive to a changes in the throughput rate as well as the extrusion temperature and is relatively unperturbed by changes in the melt intrinsic viscosity. But other changes exert only moderate influence in determining the freeze-line location [21]. Since the as-spun fiber quality is uniquely determined by its birefringence, which in turn is directly related to stress at the freeze-line, so the degree of sensitivity of the as-spun fiber properties changes in these process variables are the same as that of stress at the freeze-line [9, 17, 20].

4. Process implications

The information obtained from the sensitivity analysis provides good insight for identifying the critical process with associated level of risk [3]. The process for controlling the as-spun filament orientation requires critical process parameters like extrusion temperature, intrinsic viscosity of the polymer melt take-up velocity and melt flow rate. These parameters need to be taken into consideration, unless the control process quality is having issues as discussed below [14].

If there is an increase in temperature and/or a decrease in melt intrinsic viscosity, the spinline stress is being easily reduced, which affects the stretch ability as well as final fiber quality [5]. These higher sensitivity of the spinline stress in response to extrusion temperature has important implications for maintaining uniform product quality in a multiposition commercial plant with each position carrying multiple hole spinnerets [8, 12]. As shown in **Figure 4**, Curve 4, a variation of about 3°C in quench air temperature profile of the spinneret represents a 1% change in the extrusion temperature; but this could result in about 10% variation in the spinline stress by increasing the coefficient of variation of elongation [23]. So, having static mixers upstream of the spin pack is the best way for delivering a thermally homogeneous melt to the spinnerets [8, 12, 29]. Both the melt flow rate and the take-up velocity can also affect as-spun filament quality. This is due to, increase in take-up velocity at a constant flow rate results in increase orientation due to enhanced stretching. But for a constant take-up velocity, the orientation is reduced as the flow rate is enhanced. Because the filament denier increases rapidly with increase in flow rate, and even the spinline tension actually decreases proportionally with a net effect in a reduction in spinline stress as throughput is increased [3, 5]. By controlling such process variables (i.e., the melt flow rate and the take-up speed), it is possible to produce products over a range of denier and tenacity if needed [15, 23]. In addition, if the process is a batch process, the moisture content needs to be controlled less than 0.005% and even a moisture level of 0.01% could lower the polymer intrinsic viscosity from 0.6 to 0.56. In case if the change in intrinsic viscosity is 7%, which leads to a 35% change in spin line stress, this thereby affecting spinnability and product quality that desired [14].

In plants with continuous polymerization, variation in polymer intrinsic viscosity may also result from reactor perturbation [12]. Therefore, incorporation of

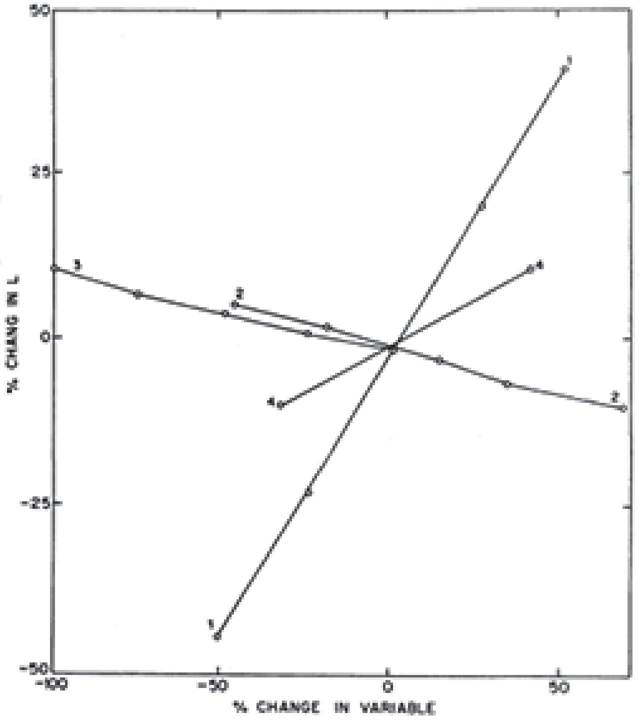

Figure 5.
Sensitivity plot for freeze-line location. The various curves are for changes in (1) melt flow rate, (2) take-up velocity, (3) quench air velocity, and (4) quench air temperature [3, 23].

an on-line viscometer to monitor the melt quality is likely to be a necessary instrumentation. There are different ways of increasing productivity. One approach is to use a process optimization discussed above, i.e., by changing the process variables to find optimum solution. The other approach is to increase in the number of holes in the spinneret by 30% [16]. If possible, as per hole layout guidelines depend on the investment to manipulate such multi-hole spinneret [16, 23, 29]. The location of the freeze-line has critical practical implications for spinline stability and product uniformity in multifilament spinning air turbulence [1, 12, 23]. An incorrect location of the freeze-line can lead to filament breakage and/or fused filaments resulting in process interruptions and poor product quality. Reducing the quench air temperature from 25 to 15°C show 40% change in the filaments stability by moving the freeze-line closer to the spinneret without a significant effect on the structural parameter like orientation, this makes it be fewer disturbances to air [23]. The take-up velocity is not the most dominant controlling variable for orientation development since its process implication does not have much impact on spun-fiber.

5. Stress-orientation relationship for PET

The Dutta Nadkarni simulation package is recommended for simulation of the melt spinning process [5, 23, 29]. Before we use the computer simulation for spinning process optimization, it is important to develop a way to quantify the correlation between the spinline stress and the as-spun filament orientation, such that the operator can confirm its validity over a wide range of spinning process parameters in current industrial operations is the data are collected from three different plants for computing the spinline stress, stress at the freeze-line [13, 14]. **Table 2** summarizes the industrial data collected. Using the data birefringence's, of the as-spun filaments orientation are measured experimentally.

$$\sigma_L = 2.526 \times 10^{-9}\left(\Delta n^{1.265}\right) \qquad (10)$$

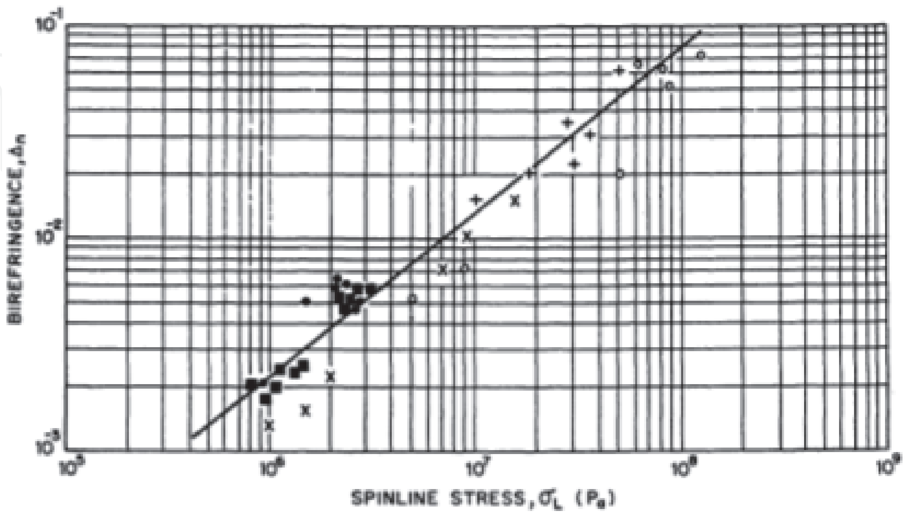

Figure 6.
Variation of birefringence with principal normal stress difference at the freeze-line. Filled symbols represent data collected from various industrial operations from India while the other symbols represent other published data [23]. The birefringence's value is correlated with linear regression analysis to fit the data and the correlation is obtained with a correlation coefficient of 0.96 for fitting 37 data points as shown in ***Figure 6*** *(straight line fit between birefringence and stress at the freeze line on the log–log plot) and Eq. (13) [14].*

Process parameter	Range	No. of variables
Intrinsic velocity	0.6–0.65	2
Extrusion temperature	275–290	3
Quenching air temperature	15–25	7
Quench air velocity	30–130	3
Spinneret hole diameter	0.2–0.3	11
Take-up velocity	500–1250	9
Throughput rate	0.5–1.0	2
Filament diameter	4.0–12.0	11

Table 2.
Parametric space covered (taken from actual industrial data).

The above equation is used as an input to the melt spinning process for optimizing the relationship between birefringence's and spinline stress for the melt-spinning of PET at speeds up to 3000 m min $^{-1}$ with a correlation coefficient of 0.96.

6. Case study for process optimization

The use of Eq. (1) along with the recommended computer simulation package for a case study to: (i) Increase the production rate, (ii) Quality of the fiber, and (iii) a new desired product developed through process optimization in spinning without affecting the fiber line processing conditions [23, 29]. Maintain the denier and orientation of the as-spun filaments at the reference levels because for a given denier product, the throughput rate and the take-up speed have to be increased proportionally which avoid downstream process optimization at the higher productivity [17]. For cases to increase in productivity changing the polymer, viscosity is not desirable rather other process parameters are desirable, such as extrusion temperature, quench air velocity and quench air temperature [18, 27]. According to the process sensitivity analysis, the orientation of the as-spun filaments, as measured by birefringence is very sensitive to changes in the spinning temperature and since the orientation related to freeze-line stress, the spinning temperature is to be changed so as to maintain freeze line stress and spin line tension at the original values [8, 13]. Quench air velocity and temperature are the other process variables that can be changed but they do not show significantly affect the spinline stress, rather on the freeze-line location in order to ensure stability of the spinline to avoid denier variation and final fiber quality [4–6]. The production rate can also be improved by a proportional increase in the number of spinneret holes with no changes in throughput per hole, take-up speed and spinning temperature and even it is best option than process optimization through changing variable [24].

The reference process parameters of a spin- line whose productivity is to be improved are summarized in **Table 3** [23] along with the process conditions determined for production rate increases of 10, 20 and 30%. The process variables provided in this table are representative of values used in a typical spinning operation, as averaged out from within the ranges given in **Table 2**. The computer simulation of Dutta and Nadkarni is used for determining the changes in the process variables when the throughput rate and take-up speed changes by 10, 20 and 30% and the effect on the response parameters, including spinline stress, spinline tension and freeze-line location, for increased productivity is shown in **Figure 7** [24].

Parameter	Original condition	Increase in melt flow rate, take up velocity(W,VL)		
		10%	20%	30%
Intrinsic velocity	0.6	0.6	0.6	0.6
Extrusion temperature	280	280	280	280
Quenching air temperature	20	20	20	20
Quench air velocity	100	100	100	100
Spinneret hole diameter	0.2	0.2	0.2	0.2
Take-up velocity	1000	1100	1200	1300
Throughput rate	0.5	0.55	0.6	0.65
Spinline stress	2.18	2.32	2.46	2.60
Spin line tension	82.8	87.5	93.8	98.0
Freeze line location	26.4	28.0	30.8	33.0

Table 3.
Effect of changes in productivity on spinline stress, tension and location of the freeze line [3].

All process variables show proportional increments with increased throughput and take-up velocity [17]. Thus, to maintain the molecular orientation and the downstream process variables constant, it is essential to have the values of spinline stress, spinline tension and freeze-line location with proper adjustment of other process variables [13]. The sensitivity analysis indicates that increasing extrusion temperature decreases the spinline stress and spinline tension but extends the freeze-line location as shown in **Figure 8** below.

When extrusion temperature is assumed to be equal to the spinneret exit temperature, there is a 10% increase in productivity. In order to return the spinline stress and tension from a 6% increase to the original level, the increase in the extrusion temperature should be approximately 1.87% [14, 27]. However, a 1.87% increases in extrusion temperature would result in a further 1.75% increase in Freeze-line location. The freeze-line location is thus sensitive to the combined

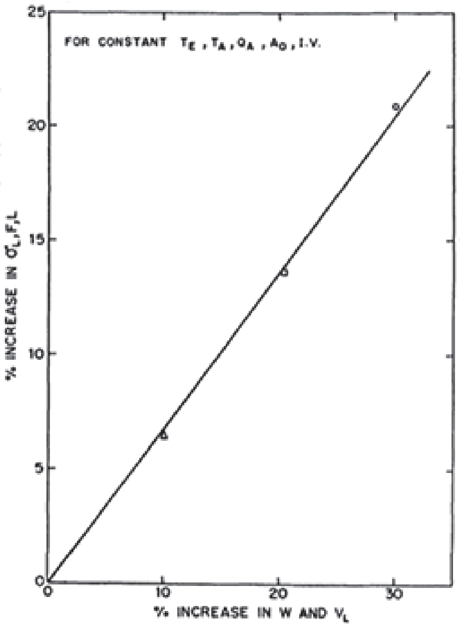

Figure 7.
Simulation results showing effect of percentage increases in throughput and take-up velocity on the spin-line stress, spin-line tension and freeze-line location.

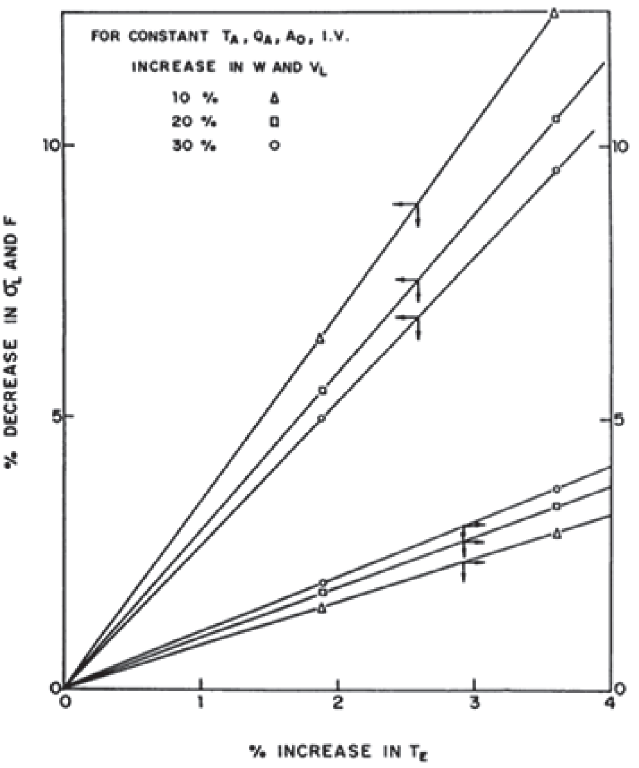

Figure 8.
Effect of percentage increase of extrusion temperature on the spinline stress, spinline tension and freeze-line location for each of 10%, 20% and 30% increase in throughput and take-up velocity.

changes in throughput rate and extrusion temperature. [15, 16] Referring to **Table 4**, although the spinline stress and tension can be brought back to the original values by a change in the extrusion temperature, the freeze-line location remains

Parameter	Reference condition intrinsic viscosity (IV) = 0.6	10% decrease in freeze line location, take up velocity (L,W)	1.9% increase in extrusion temperature (T$_E$)	45% decrease in quench air temperature (Ta)
Intrinsic velocity	0.6	0.6	0.6	0.6
Extrusion temperature	280[a]	280	285	285[a]
Quenching air temperature	20[a]	20	20	11[a]
Quench air velocity	100	100	100	100
Spinneret hole diameter	0.2	0.2	0.2	0.2
Take-up velocity	1000[a]	1100	1100	1100[a]
Throughput rate	0.5[a]	0.55	0.55	0.55[a]
Spin line stress	2.18[b]	2.32	2.20	2.19[b]
Spin line tension	82.8[b]	87.9	83.3	82.9[b]
Freeze line location	26.4[b]	28.0	28.9	26.8[b]

[a] *Parametric values changed to achieve a 10% increase in productivity for constant product quality.*
[b] *Values held constant to maintain product quality.*

Table 4.
Summary of process changes required obtaining a 10% productivity increase while product quality is maintained constant.

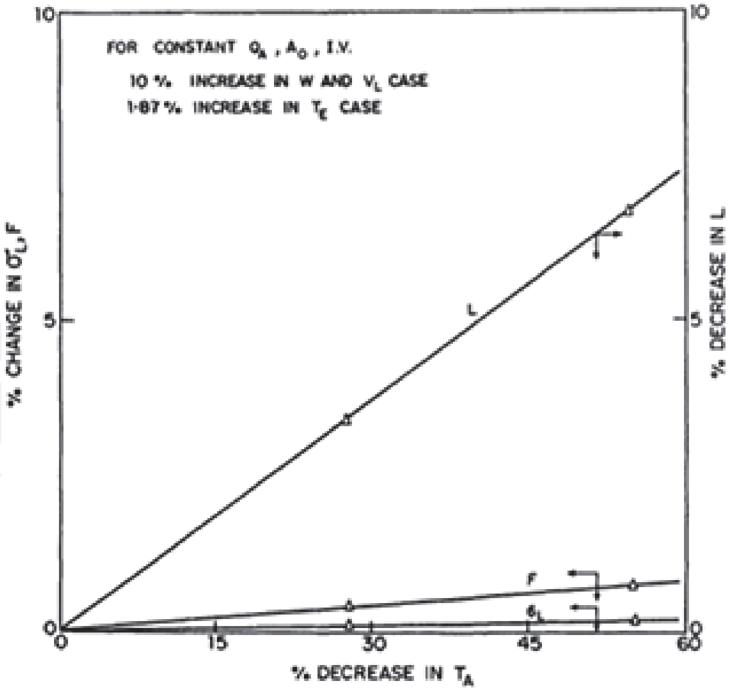

Figure 9.
Effect of percentage decrease in quench air temperature on spinline stress, spinline tension and freeze line location for the specific case of 10% increase in throughput and take-up velocity [16, 23].

different from the original value by about 9.5%. The location of the freeze-line can affect the spinline stability and product uniformity [13, 14]. Hence its retention at the original value is desirable. A process variable is to be sought, which would move the location of the freeze line closer to the spinneret without any significant changes in either spinline stress or Freeze-line location. The quench air temperature is known to influence freeze-line location to a greater extent relative to spinline tension and spinline stress and can be effectively used for stabilizing the spinline. From **Figure 9** it is seen that to move the freeze- line location by about 8.0%, the quench air temperature has to be decreased by about 45%. Furthermore, the effect of this process change on spinline stress and freeze line location is insignificant. The entire exercise is summarized in **Table 4**, which indicates the changes in process variables required to increase productivity while maintaining the denier, orientation and stability of the spinline [14].

7. Case study for product development of low pill fibers

Lowering the intrinsic viscosity or molecular weight by having drawn fiber denier of 1.2 held constant to make the downstream process variables at constant values [10, 25] (**Table 5**). Because of this the changeable variables, it is required to lower the draw ratio to 3.5 from reference value to prevent fiber breakage in downstream process and this change as-spun denier from 4.5 to 4.2. Due to 8.3% decreases in intrinsic viscosity a new pill fiber is developed. However, this phenomena (decrease in spun fiber diner) causes the decrease in Spinline stress and Spinline tension, which makes melt unspinnable increases the take-up velocity and the throughput rate to new values (22.5%, 14.2% respectively), and lowering extrusion temperature to 275°C. This is a way to increase the Spinline tress with as-spun denier at a value of 4.2. Freeze-line location has effect on the spinline stability and product uniformity stress [30]. However having 50% decreases in quench air temperature from reference value, to maintain the spinline stress and freeze-line

Parameter	Reference condition intrinsic viscosity (IV) = 0.6	8.3% decrease in melt intrinsic viscosity (IV)	22.5% increase in take up velocity (V_L) 14.2% increase in melt flow rate (W)	1.8% decrease in extrusion temperature (T_E)	50% decrease in quench air temperature (T_a)
Intrinsic velocity	0.6[a]	0.55	0.55	0.55	0.55[a]
Extrusion temperature	280[a]	280	280	275	275[a]
Quenching air temperature	20[a]	20	20	20	10[a]
Quench air velocity	100	100	100	100	100
Spinneret hole diameter	0.2	0.2	0.2	0.2	0.2
Take-up velocity	1000[a]	1000	1225	1225	1225[a]
Throughput rate	0.5[a]	0.5	0.571	0.571	0.571[a]
Spin line stress	2.18[b]	1.63	2.05	2.16	2.18[b]
Spin line tension	82.8[a]	61.8	72.5	76.6	76.9[a]
Freeze line location	26.4[a]	26.3	29.6	29.3	26.5[a]
As-spun fiber denier	4.5[a]	4.5	4.2	4.2	4.2[a]
Drawn fiber denier	1.2[b]	1.2	1.2	1.2	1.2[b]
Draw ratio	3.75[a]	3.75	3.5	3.5	3.5[a]

[a] *Parametric values changed to achieve low pill fiber product.*
[b] *Values held constant to maintain the downstream process variables at constant values.*

Table 5.
Summary of process changes required obtaining low pill fibers without affecting downstream variables [23].

location at the original values, we need to move the location of the freeze-line closer to the spinneret [23–25, 28].

8. Conclusion

The mechanical property of fiber is highly governed by the orientation level in the thread line. However, this structural parameter is heavily affected by the melting process as shown in the sensitivity analysis above with different level of effects. According to the above analysis, it is shown that the molecular orientation developed in a melt flow in spinning process is governed by the spin-line stress (stress at freeze line). A mathematical equation, which is an input for the simulation is developed according to a given quantitative data, shows a linear relationship between the orientation and stress levels. The simulation results are correlated with the variables associated with the spin-line stress to determine if the stated assumptions are in agreement with the simulation results. The combination of the process simulation and stress-orientation relationship gives us a procedure for identifying and simulating the important spinning process variables that would affect the spin-line stress, and hence the mechanical properties and fiber line processability of the as-spun filaments. Once the effect is simulated the process optimization is done by changing the process variables according to the final property desired. Therefore, the process optimization can be achieved using SOS perspective and computer simulation. This is a good advancement in melt spinning to achieve the process optimization. The future work will tell on computer simulation and modeling of manmade fibers and their parameters based on systems of system perspective.

Notations

A_O	initial cross sectional area
T_O	spinneret exit temperature
A(x)	cross sectional area at (x) distance
T(x)	spinneret temperature at (x) distance
Va	quench air velocity
V_L	final velocity
Ta	quenches air temperature
A_L	final cross sectional area
X	distance from spinneret
L	freeze line location
Tg	glass transition temperature
n	birefringence
σ_L	stress at freeze line

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