Dynamics of the Threadline in Melt Spinning*

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Synopsis

In the nylon 6 melt spinning process at speeds of 900 and 1200 m/min the quenching is done in a stepwise manner. The effect on physical data of the drawn yarn is investigated and correlation between quench height, water takeup, and boiloff shrinkage discussed. Length changes across the takeup machine are also measured as function of quench height and seem to correlate with physical data. The speed of length changes for both finished and unfinished yarn as a function of quench height suggests a molecular oscillation along the spinning line rather than a continuous orientation of the molecular structures. A secondary disorientation zone is defined.

INTRODUCTION

For the melt spinning of synthetic fibers, uniformity in every respect is extremely important. Unfortunately many parameters contribute to irregularity of the filament, which most commonly is measured by the Uster diagram. Whereas many of the mechanical and mostly periodic influences, like take-up traverse stroke or ringrail movement, are easy to identify, the cause of many others is still unknown.

This article will deal with irregularities mostly of a periodic nature, seen during the melt spinning process itself, and will finally address the molecular dynamics during fiber formation.

EXPERIMENTAL

Mechanical Influences

By means of a vibrationmeter applied at different locations of a melt spinning machine, the cycles were identified which are shown in Table I. Under the spinning conditions of 795 m/min and a draw ratio of 3.35, they were expected to yield periods over the indicated length. Analysis of the yarn by using the Uster spectrogram showed not a single frequency of the machinery to correlate with the yarn irregularities.

In a separate experiment we mechanically imparted oscillations onto a spinning threadline between 100 and 3800 cycles/min yielding no correlation to the Uster spectrogram until 55 Hz were reached.

In a paper presented at the International Symposium of Synthetic Fibers in Kalinin, 1986, Zhiganov[1] et al. investigated beyond the mechanical factors also the influence of temperature, extrusion speed, quenching, and melt viscosity as

*Dedicated to Professor Dr. Helmut Doerfel on the occasion of his 60th birthday.

Journal of Applied Polymer Science, Vol. 35, 953–963 (1988)
 CCC 0021-8995/88/040953-11$04.00

TABLE I
Oscillations Found at the Equipment of a Melt Spinning Plant

Point measured	(cycles/min)	(Hz)	Spectrogram	
			Predicted	Found
A. Spinnerette pack bolt	18,000	300	5.8 in.	No
	3,500	58	29.9 in.	No
	1,200	20	2.4 yds.	No
B. Quench cabinet	7,800	130	13.4 in.	No
	2,400	40	1.21 yds.	No
C. Quench cabinet base	1,200	20	2.4 yds.	No
D. Convergence guide	2,400	40	1.21 yds.	No
E. Ceramic guide above kiss roll	5,000	83	20.9 in.	No
	1,750	28	1.57 yds.	No

causes for instability during melt spinning. Also draw resonance was included. The mathematical treatment confirmed only one dominating diameter frequency around 17 Hz. This was attributed to mechanically induced spinline vibrations.

The difficulty in correlating mechanical vibrations with mass irregularities along the fiber suggests that other parameters may be more influential.

Nonmechanical Influences

Whereas the spinning filament shows relatively little sensitivity to imparted mechanical vibrations, the spinning threadline seems easier to be destabilized by variations in temperature and take-up speed, as shown by Kase and Araki.[2]

Hence temperature changes during quenching suggest itself as a potential cause for fiber irregularities. Unfortunately, air-quench is one of the production steps which is usually more difficult to control.

The influence of cross-blowing air is described widely,[3] but even the brilliant investigation by Fourne[4] yielded the conclusion that turbulences in the cross-blowing air accounted only for 0.68% of the denier variations. Too many additional influences blur the picture. Han and Apte[5] investigating cooling and elasticity, as well as Freeman and Coplan,[6] point rightfully to elastic oscillations, either under draw resonance or through the dye swell effect. Similar investigations were carried out by Ziabicki[7] and many others. It is therefore very likely that the dynamics of the molecular arrangements will best explain most of the irregularities along the fiber.

Unfortunately, the changes in structure occur too fast to be analyzed in all respects, and the work addressing measurement of birefringence, diameter variation, tension, temperature, and on-line X-ray do not reveal enough to describe completely the actual filament status and irregularities which later on develop into fiber defects.

Our method of stepwise "freezing" these molecular stages and measuring the response of their inner tensions to water absorption, length changes, and boil off shrinkage seems to close the gap in part.

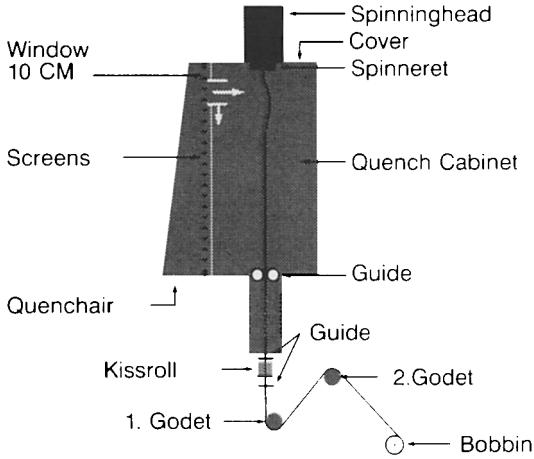

Fig. 1. Spinning of 40/10 nylon 6 filament at take-up speed of 900 mpm.

It will help to make visible a type of molecular oscillation not being assumed under the conditions of low sheer and normal spinning speeds. Also, it reveals the continuity between necking and nonnecking deformation, which sometimes has been questioned.[8]

The Role of Inner Tensions

Figure 1 shows the apparatus used to effect the temperature at different stages of fiber formation.[9] The 10 cm wide window was moved down in steps of 10 cm after obtaining two full bobbins at each position level. The fibers then were cold drawn and tested. We measured: Denier, elongation, tenacity, boiling water shrinkage, water content, spin finish, bobbin formation, dyeability of knitted hose with Ortolan Blue G and Uster evenness both drawn and undrawn.

The graph in Figure 2 shows the values obtained on the drawn yarn. It is noteworthy that the water take-up of the filament (or better, its water retention) can vary from 3 to 4.5% at the same revolution of the spin finish roll. A look at the boiling water shrinkage reveals a range of 11–15% "everything constant" except the quench level. As can be seen, both water uptake and shrinkage are running somewhat in a reciprocal relationship.

Where water uptake was high and boil-off shrinkage low, we obtained the best bobbin buildup, the (relatively) best Uster evenness, the dye uniformity. The opposite holds true for low water takeup and high boiling water shrinkage.

Therefore another "oscillation," so to speak, seems to be revealed by the response to water pickup and boil-off shrinkage, which directly relates to molecular tensions.

It may be assumed that the zones with low boil-off shrinkage, that means between 10 and 30 cm as well as 90–120 cm quench distance, represent a more relaxed amorphous structure. The water has easier access to these areas and therefore the pickup (or better, holdback) is higher. To the contrary: Internal tensions *do* drive molecular rearrangements and crystallization.[10]

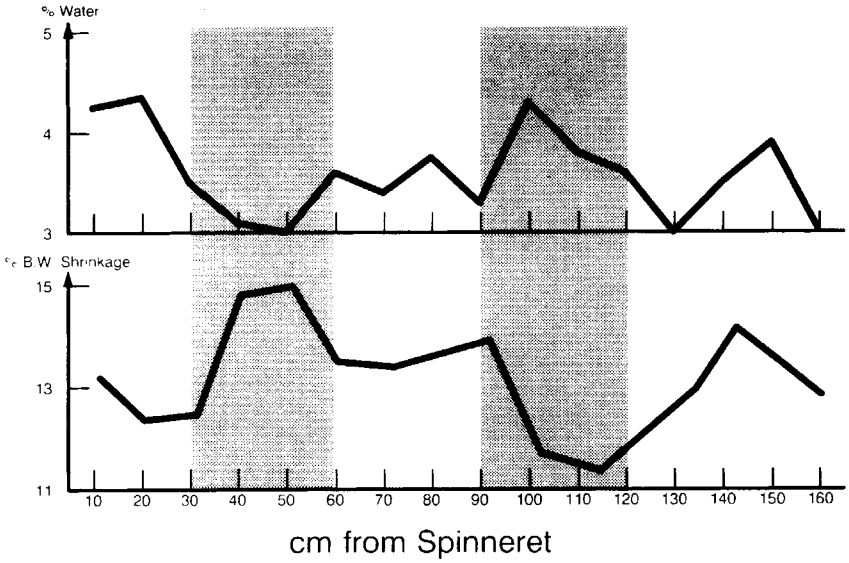

Fig. 2. Stepwise quenching and its effect on physical data.

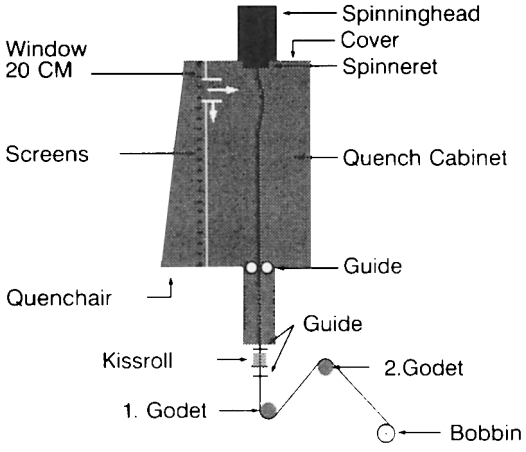

Fig. 3. Spinning of 40/10 nylon 6 filament at take-up speed of 1200 mpm.

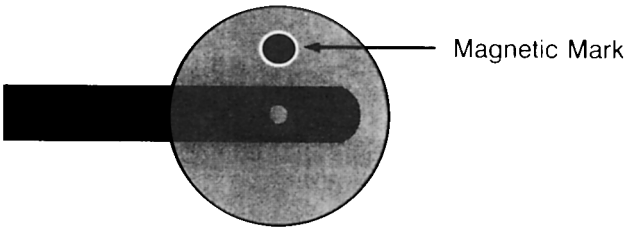

Fig. 4. Device for length measurement.

Under the influence of water at the spin finish roll, the glass transition temperature is lowered. The filaments with higher internal tension will accelerate their crystallization, increase density, and thus hamper water from entering the filament as freely. The structure may also be considered as being less of a sponge to hold the water back during wind up.

The graphs in Figure 2 show this happening for 30–60 cm and beyond 130 cm. This is called a "blocking effect." Indeed—and this is one of the most important practical consequences—these variations of water take-up (or better, retention) at constant finish application and the induced differences on fiber length cause the classical problems in a melt-spinning plant, with bad bobbin formation and poor filament quality.

The speed of all these changes is less than 1/100 of a second and suggests an analogy to the photographic process. Unstable high energy systems (AgBr or tensioned regions) are hit by an initiator (light or water) to spread out

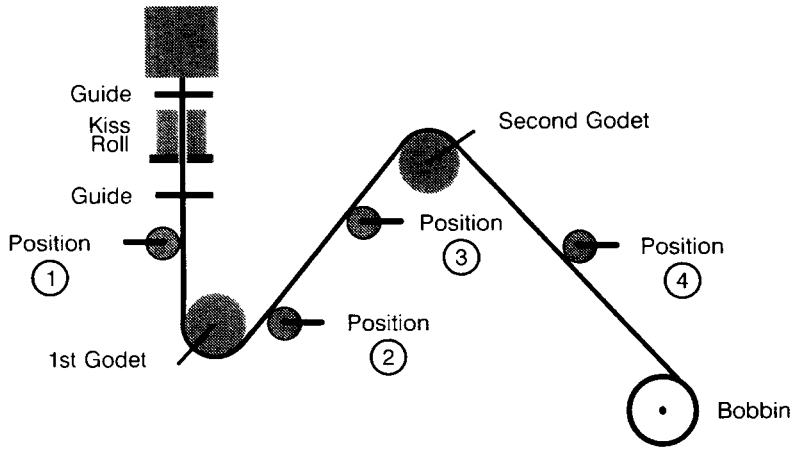

Fig. 5. Yarn path at take-up with positions for measurement.

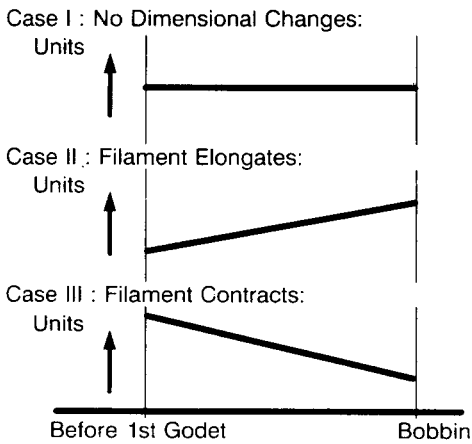

Fig. 6. Length changes in take-up as seen by digital length counter.

immediately a series of new lower energy structures (Ag or "crystallized" polymer respectively).

Consequences for Length Changes during Melt Spinning

As inner tensions, temperature variations, as well as structural rearrangements cause dimensional changes of a filament, especially under the influence of water, measuring of length changes directly on the running filament are supposed to show a similar pattern with shrinkage and water pick up.[11]

The experimental setup described by Figure 1 was modified as shown in Figure 3. Then the revolutions of a rotating magnetic device were used to record length changes (Fig. 4). This yarn driven device was placed at different positions of the takeup machine (Fig. 5). A coefficient of variation of 0.03% was obtained. Figure 6 describes how any length change would present itself in the digital code.

In the case of a steel wire with no change in length, the same number of revolutions would be seen on the magnetic wheel at each of the four positions.

If the yarn increases its length over the take-up section and is being wound up at constant speed, there will be less demand from the spinneret above, and the revolution at point 1 will drop. A rising profile thus will indicate lengthening of the filament.

The opposite holds true for the case of shrinkage, which causes a falling digital profile.

A profile of speed or length changes, respectively, across the takeup machine can be plotted for a series of quenching distances from the spinneret. For reference, the filament bypassed the spin finish roll for a short bobbin without finish.

Figures 7 and 8 show the results:

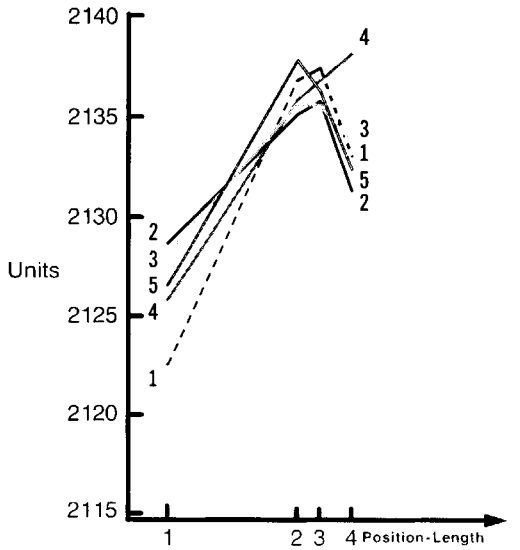

Fig. 7. Length changes on take-up machine with spin finish.

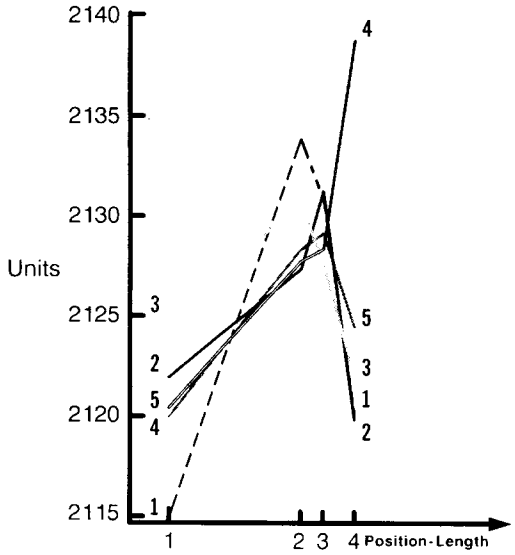

Fig. 8. Length changes on take-up machine without spin finish.

These curves typically indicate elongation in the first and second part. However, there are "bad conditions"—graph 4—among them, which excels even more without finish. On comparing both graphs, it is noted that the curves with finish start at a higher level, suggesting less elongation compared to those with "no finish."

The "good samples" also have completed their shrinkage before the bobbin; meanwhile the bad ones mostly still elongate before windup. This causes wraps, trapped filaments, drop in winding tension, and bad bobbin buildup.

Speed of Length Changes

If it is assumed that the amount of water "take-up" is inversely related to the internal tensions of the structures, then the tension difference between these structures must show up also in the *speed* of water absorption, and this in turn as the speed of dimensional change.

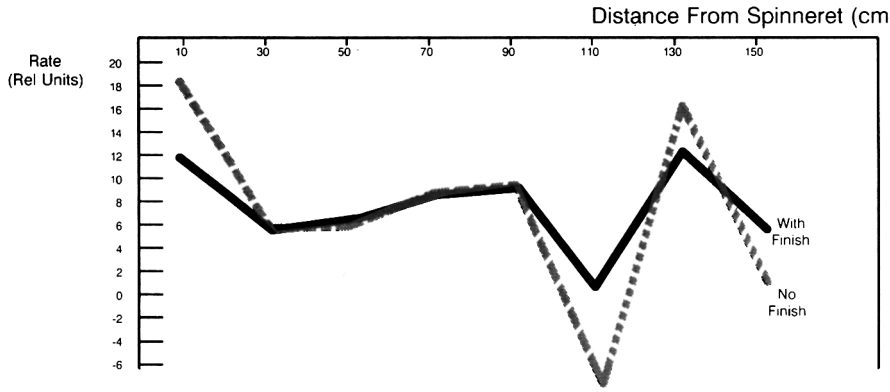

Fig. 9. Relative speed of length changes between measurement positions 1 and 2.

This speed of length change can be obtained from the slope of the curves in Figures 7 and 8, which generates the graph shown in Figure 9.

The speed of length changes as a function of quench level is the already familiar pattern seen with boil-off shrinkage and water take-up. There are two maxima: one at the beginning and one at the end of the tested quenching range, each being followed by a substantial drop of the represented parameter.

Interestingly enough, the influence of water smoothes the profile of length changes at any quench height; it obviously has a compensatory influence.

What is surprising is the sharp distinction of zones, in the solidification being made visible by this method and above all its nonlinearity.

DISCUSSION

This finding commands an apology insofar as most scientists dealing with the mathematical description of the spinning line did not yet provide for this. The thin filament theory by Kase[12] is based upon the "one shot stretching of fine fluid threads" and has almost no provisions for such irregularities or neck formation.

However, this could hardly be expected, as it was only recently that neck formation in the spinning of polyester was proven. The same applies to the irregularity of the temperature profile for high speed polyester quoted by Ziabicki from Katayama and Yoon.[13]

It should also not be overlooked that the thermophysical behaviors of polymers under tension is quite complex and provides for the inversion of certain functions like the internal energy or thermal expansion coefficient as described by Godovsky.[14]

On the other hand, oscillations of tension and diameter based on thermophysical effects (e.g., "stick slip"), especially at slow drawing speeds, are known. They become more pronounced if the heat generated by the drawing is quickly dissipated, e.g., in hydrogen.[15]

It was taken for granted that this phenomenon seen on the Instron tester would not apply to spinning and drawing at the higher production speeds, as ample heat is generated or—as in the case of polyester—can be externally provided.

Our experimental findings seem to cast some doubt on this assumption. Of course, there are other excellent investigations which address the parameters influencing fiber formation.[16-18] Compared to those papers, our data suggest even more internal structural irregularity by defining and locating a *secondary disorientation zone*. This is different from the "classical" picture of fiber formation described by, e.g., Shimizu, Okui, and Kikutani[19] or Katayama et al.[20] It seems that the "clear cut between uniform and necklike deformation," mentioned in the literature,[8] gets blurred.

Redisorientation under crystallization is described also by Ziabicki,[21] Abhiraman,[22] and many others. It seems to be needed for the storage of crystallization energy in nonequilibrium systems. Glansdorff, Prigogine, and Lindenmeier[23] refer to so-called dissipative structures. Recent findings describe a decreasing orientation in the amorphous phase as function from spinneret distance.[22]

What seems to be new is the precise definition of the location and relative status of inner tension for each step in the quenching process.

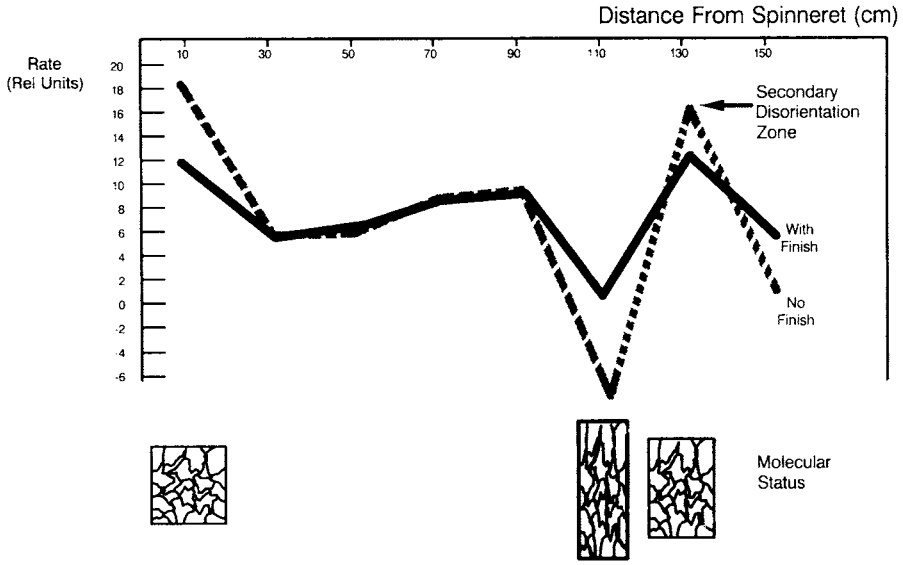

Fig. 10. Interpretation of relative speed of length changes.

INTERPRETATION

In spite of the fact that the experimental setups under 2 and 3 were not identical, similarities in kind of the results may allow a common interpretation. Starting from the Poynting Thomson model,[24] plastic and elastic deformations take place side by side. In Figure 10 it could mean the following for the respective quenching distances:

0–20 cm. The molecules relax in the Barus-zone, open structures with little tension are frozen in preferably and cause high water take-up and low boil-off shrinkage. The water slows the elongation speed, probably by cooling, and perhaps some densification of isotropic structures occur.

30–90 cm. Mostly rubber-elastic with stages of comparable energy potentials, oscillations in molecular network, some anisotropy neutralizes the contracting influence of water, also blocking it out. Water uptake is lower, boiling shrinkage higher, and the Uster is bad (see Fig. 11).

110 cm. Molecules are stretched to full elastic state, more resistance to pull, speed increase goes down, but water hits more anisotropic structures, and

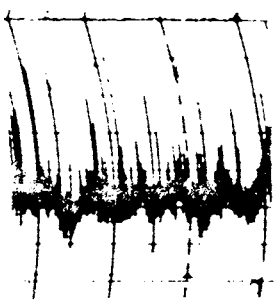

Fig. 11. Uster diagram nylon 6, 40/10 from threadline representing section of high molecular tension.

therefore lengthens the filament. Water pick-up is low, tensions not fully relaxable, boiling water shrinkage is high, and "yarn works on bobbin." High inner frictions, as described by Mozejko, Mezirova, and Filbert,[25] generate heat. The heat starts an oscillation of the orientation and so does the melt temperature and glass transition temperature with it. This zone exerts the highest gravitational forces on the structures.

130 cm. The heat provided by orientation and onset of crystallization leads to new molecular relaxation; excess energy is stored in the more disoriented amorphous phase. Water take-up rises, more plasticity eases speed increase. The boiling water shrinkage drops. We deal with less tensioned structures, good Usters, and good bobbin buildup. Similarity to the 0–20 cm quench arise; one cycle of the frequence is complete.

150 cm. The now thinner filament solidifies quickly in a newly tensioned state, perhaps similar to the 30–90 cm range, shrinkage arises, water pickup drops, its effect on speed change is only half of the one in the 110 cm range. The filament is cool, the oscillation of the molecules dies out.

These findings shed light on the cause of many quality and wind-up problems experienced in conventional melt spinning plants and will hopefully help many people around the world.

CONCLUSIONS

1. The molecular structure under the spinneret oscillates.
2. A secondary disorientation zone can be defined and localized.
3. There seems to be a continuum between nonnecking and necking conditions.
4. The measurements of water take-up, boiling water shrinkage, and simultaneous length changes, including their relative speeds, allow judgments about the development of inner tensions during the solidification of the spinning polymer. In our case, they suggest a repetitive pattern with a wavelength between 15 and 20 Hz.
5. The method allows us to directly estimate relaxation times; in our case, around 1/100 of a second.
6. The method allows to better distinguish each zone of the filament formation often discussed in the literature.[21]
7. A detailed knowledge of structure development and correspondingly adapted quenching conditions may well provide not only for technical process improvements, but also allow tailoring of fibers with advanced properties.
8. As no quantitative theory exists currently to account for extension of crystallizing oriented structures,[22] it is hoped that a better segmentation of the molecular dynamics as addressed in this paper will facilitate this.

I want to thank Mark S. Johnson for his contribution and my colleagues at BASF for their support.

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Received June 22, 1987
Accepted June 26, 1987