A Unified Concept of Melt Flow Instability During Extrusion

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Synopsis

The mechanism of melt flow instability at drawdown rates below and up to that necessary to compensate for die swell and at drawdown rates exceeding the former is explained with the aid of diagrams and appropriate comment. It is suggested that there is no fundamental difference between the causes of commonly encountered extrudate defects and "draw resonance" which appears in fiber spinning at excessive drawdown rates. It is argued that both are manifestations of viscoelastic phenomena which affect extrudate appearance either not at all due to effective suppression or which give rise to defects of increasing severity when control of the process—including die design and proper consideration of the forces at the die/melt interface—is inadequate.

INTRODUCTION

Melt fracture has been thoroughly debated during the last two decades. Apart from a brief review by the writer[8] in 1968, attention is drawn to the work of Tordella,[1,2] Bagley,[3] Clegg,[4] Cogswell and Lamb,[5] and especially of White[6] and Han.[7] We now wish to present, by means of diagrams and annotations, our view of progressive changes in extrudate flow phenomenology and associated defects which are thought to be induced by increases in extrusion pressure and/or increases in the tension of the melt within the die itself as a result of increasing drawdown beyond a critical threshold.

DIAGRAMS

Two series of diagrams are presented. The first series, numbered 1 through 6, represents a progressive increase in applied pressure (shear stress) at zero drawdown or at a drawdown not exceeding that necessary to compensate for die swell (Fig. 1).

In Figure 1, diagram 1 depicts stable laminar flow with eddying currents of stagnant flow at the shoulder of the die entrance. Drawdown is absent or slight, die swell being prominent. Diagram 2 shows the development of flow instability at the die entrance, but the shear stress is not, as yet, excessive. The dwell time of the melt in the die channel is therefore sufficient to exceed the relaxation time of the melt. This ensures that uniaxial laminar flow is reestablished and that the elastic memory of the flow instability which the melt has been subjected to upstream is annealed out. As a consequence, the extrudate shows no defect.

In 3A, the residence time of melt in the die is less than the relaxation time because of an excessive increase in the applied pressure (shear stress). This also affects the adhesion of melt to die wall and thus makes snapback possible. Snapback is a cyclic oscillating retraction of melt in an upstream direction due to the recovery of elastic strain. The greater that strain, the greater will be the

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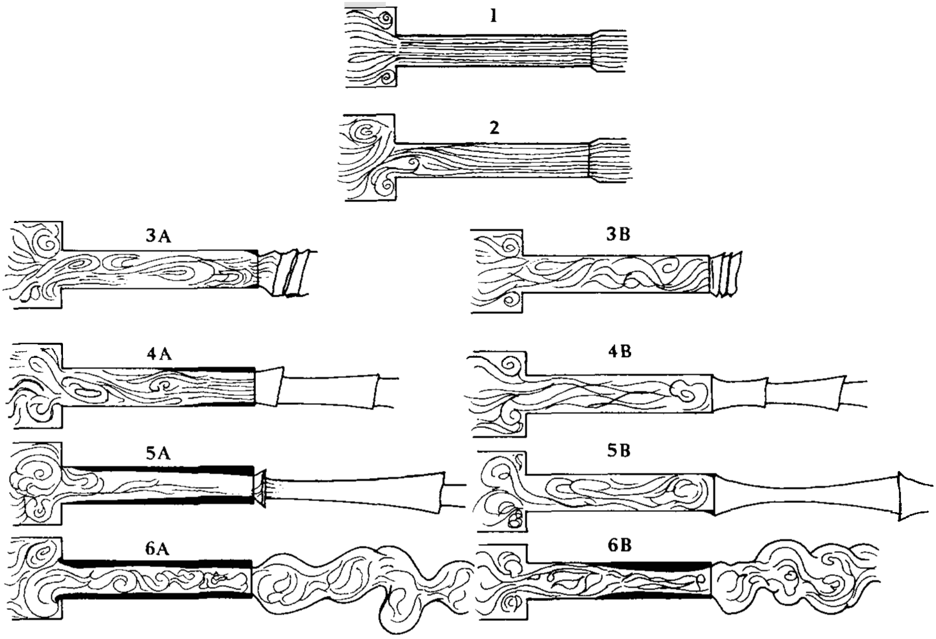

Fig. 1. Extrusion with no drawdown (1, 2, 3A through 6A) or with moderate drawdown such that snapback is prevented (3B, 4B) or reduced (5B, 6B).

retraction amplitude and the larger will be the mass per cycle. This shows itself by increasingly severe extrudate defects, from surface mattness through "orange peel" and "sharkskin" to "corkscrewing" and "bambooing" (4A, 5A). In 6A, the upstream snapback amplitude has become so large that it covers the entire die length right up to the site of primary flow instability. When this occurs, a blob of turbulent or stagnant material slips into the die and is carried some variable distance downstream. The die channel is thus partially refilled until the next snapback event is triggered. The snapback cycles themselves are now arythmic, and the correspondingly variable elastic recovery results in variable masses (and shapes!) per cycle. At this stage gross distortion of extrudate is observed, and the extrudate ceases to bear much resemblance to the profile of the die orifice.

While 3A through 6A depict the maximum amplitude of the snapback cycle, 3B through 6B show the other extreme of that cycle, namely, the situation just prior to the triggering of snapback.

The second series of diagrams (Fig. 2) represents extrusion at constant pressure and at increasing drawdown rates. Drawdown not only reduces die swell for obvious reasons. It also orients the flow units, aligning them in an axial direction, assists the return of the isovels to an axial distribution, and counteracts snapback. In so doing it brings about steady-state conditions as shown in diagram 7. By the same token, the appearance of extrudate defects is either altogether prevented or, if present, disguised and rendered unidentifiable as the filament is smoothed out by stretching.

As drawdown is further increased, the tension will increase to a magnitude sufficient to cause dehesion of melt from the die wall in an upstream direction. This is a logical consequence of the rapid increase in viscosity as the emerging

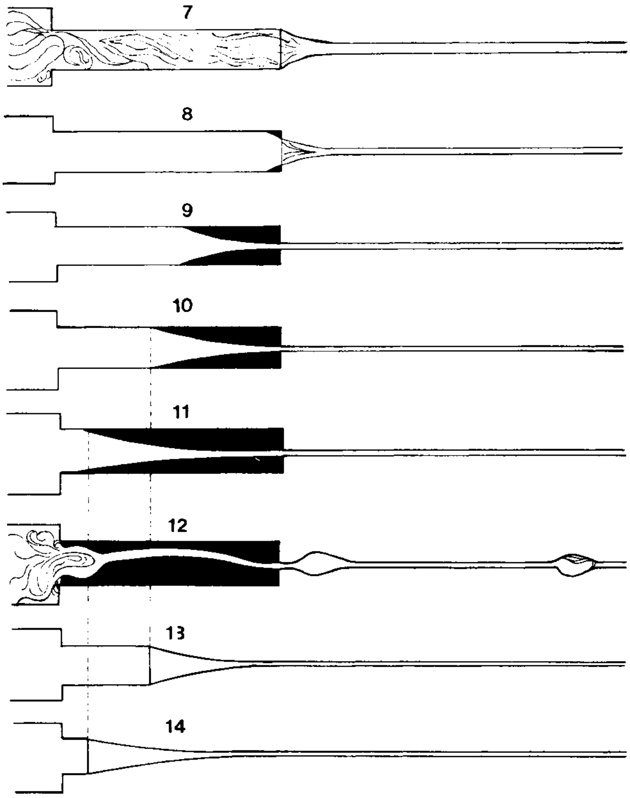

Fig. 2. Extrusion with large drawdown. (Note that 13 and 14 represent the "effective die lengths" of 10 and 11, respectively.)

filament cools. The melt inside the die channel then requires substantially less force to effect a reduction in cross-sectional area than the material further down the spinline. This causes progressively further dehesion of melt in an upstream direction as the degree of drawdown is increased (8 through 11).

As distinct from dehesion due to elastic recovery of the strain produced at the die entrance under pressure (Fig. 1), dehesion in Figure 2 is tension induced and the strain cannot be relieved by a snapback mechanism. Instead, a noncyclic steady-state condition is established under which the monofilament or fiber is still perfectly regular, even though the die length is *effectively* reduced—see diagram 10, which corresponds to the die length of diagram 13 and diagram 11, which corresponds to that of diagram 14.

When drawdown becomes excessive, melt dehesion results in producing a die of effective zero length, and the filament is drawn directly out of the unstable die entry region. At this moment an irregular blob will be pulled into the die, elastic relaxation will occur, and the stresses leading to the next cycle will immediately start to build up again. We thus witness a return to a cyclic sequence of melt dehesion and readhesion, this time, however, in the *absence* of snapback (12). This is the effect which Han and others describe as "draw resonance." It is observed when fiber is spun at excessively high drawdown, a drawdown which is easily reached in a process in which high takeoff rates are necessary and characteristic. It is thus possible to identify critical drawdown rates which will cause the appearance of regularly spaced nodules in the extrudate when it is reached and exceeded and to regard this critical drawdown rate as the criterion for "draw resonance."

CONCLUSIONS

(1) *All* flow instability originates at the die entrance.

(2) In the absence of drawdown (or with drawdown not exceeding that required to compensate for die swell), surface defect will be absent (1 and 2) or relatively mild (3), more severe (4 and 5), or gross (6) depending on the applied extrusion pressure and on the magnitude of the elastic strain imposed on the melt as a consequence. The defects are triggered by snapback in an upstream direction of the material from the die exit, especially if adhesion of melt to die wall is weak. The elastic strain itself is generated at the die entry, especially at high screw speeds and correspondingly high pressures and shear stresses. When snapback reaches that site of primary flow instability, the extrudate will cease to show all regularity, even the regularity of cyclic rhythmic repetition which is already unacceptable in an extrudate.

(3) In the presence of drawdown greater than that necessary to compensate for die swell, dehesion will again be induced in an upstream direction from the die exit. However, under constant tension no snapback can occur and no cyclic discontinuities will appear unless some critical drawdown rate is reached and exceeded.

(4) When exceeding the critical drawdown rate, the die will momentarily reach effective zero length and the fiber, still in its melt stage, will join up with the disturbed flow regime at the die entrance and cause the emergence of nodules at regular cyclic intervals. The conditions for "draw resonance" have been reached.

(5) We take the view that "melt fracture" and "draw resonance" are *not* distinct and separate flow instability phenomena. We believe that both are caused, in the first place, by elastic effects that have their origin at the die entrance, irrespective of whether it shows itself as extrudate defects of variable degree of severity due to elastic recovery (snapback) when the die contents are under pressure or whether there is an abrupt transition from regular to cyclically knobbly fiber as the drawdown rate (and with it the tension in the die channel) becomes excessive and the effective die length is reduced to zero. The only difference is that in the latter case there is no *gradual escalation* in the severity of surface defects—the cyclic knobbliness occurs abruptly under excessive tension, just as gross melt fracture in ordinary extrusion without much drawdown occurs under excessive pressure.

(6) It is worth noting that the worst effects of melt fracture can be avoided by tapering the die inlet and by slightly tapering the die channel itself.

(7) Finally, it is pointed out that the specific adhesion of polymer melts to the die metal under various stresses and at various temperatures undoubtedly constitutes an important factor in any attempt that may be made to quantify the phenomena discussed above.

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