Surging in screw extruders

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Output uniformity is one of the main factors limiting the maximum output obtainable from a single screw plasticating extruder, and is adversely affected by surging. Several causes of surging have been identified, perhaps the most important being instabilities in the melting process. These are caused by periodic break-up of the bed of compacted solid polymer formed in the screw channel. Solid bed break-up is shown, both experimentally and theoretically, to be associated with rapid acceleration of the bed in the downstream direction parallel to the screw flight. A novel method of measuring solid bed velocity and hence acceleration is described. The theoretical model of the melting process is shown to be capable of predicting this acceleration reliably, and therefore the tendency for a particular combination of screw design, material and operating conditions to cause surging.

INTRODUCTION

The maximum useful output rate obtainable from a single screw plasticating extruder of a given size is generally determined by extrudate quality requirements. One of these requirements is for a high degree of uniformity of both material properties and temperature. Another requirement, often a more limiting one, is for a steady output rate in order to keep extrudate dimensions within tolerable limits. Variations in flow rate are accompanied by fluctuations in both pressure and temperature[1,2]. Therefore, a pressure gauge or transducer mounted in the barrel wall may detect not only a perioidic change in pressure associated with the rotation of the screw, but also a more severe variation occurring at a lower frequency[1].

Some attempts have been made to analyse and explain surging in extruders. For example, considering only the polymer after melting, Chan *et al.*[3] carried out an analysis for transient viscoelastic melt flow. Also, Kirby[4] and Krueger[5] examined the response of the melt flow in the metering section of an extruder to small disturbances in the rate of melt supply. The main limitation of these approaches is that only the tendency of the melt flow to amplify or damp out disturbances can be examined. The cause of the disturbance is not elucidated.

Turning to the feed end of the extruder, Lovegrove and Williams[6,7] showed that pressure fluctuations are unavoidably associated with the solids conveying process. These fluctuations occur at the same frequency as the screw rotation but may not be significant in magnitude compared to the overall pressures generated. Various types of mathematical models have been proposed for simulating the dynamic response of the melting process in a plasticating extruder[8,9]. Again only the response rather than the cause is studied. A number of experimental investigations of the melting process have demonstrated a link between surging and instability in the melting process which is the main subject of this paper.

There appear to be at least three different types of surging summarized as follows.

(1) Variations associated with the rotation of the screw, particularly due to the solids conveying process, and occurring at the same frequency.

(2) Fluctuations due to instabilities in the melting process and occurring at rather lower frequencies.

(3) Very slow fluctuations over periods of minutes or even hours caused by instabilities in the temperature control systems or changes in the environment.

INSTABILITIES IN THE MELTING PROCESS

The normal mechanism of melting in a screw extruder is now well established, at least for small and medium sized machines[10–13]. *Figure 1* shows a diagrammatic view of a typical channel cross-section as seen from the screw looking downstream. There are four distinct regions, namely the barrel melt film where most of the melting occurs, the screw melt film, the solid bed and the melt pool. While the motion of the barrel relative to the bed sweeps melt into the pool, melt formed in the screw film is retained there and the film thickness tends to increase. Although the width of the solid bed normally decreases as the bed moves downstream, this trend can be reversed with a screw having a rapidly tapering channel in the compression section. Indeed, Klein[14] has suggested the associated wedging effect as a direct cause of surging.

If the melting process is stable, the solid bed remains continuous in the downstream direction until either its width or

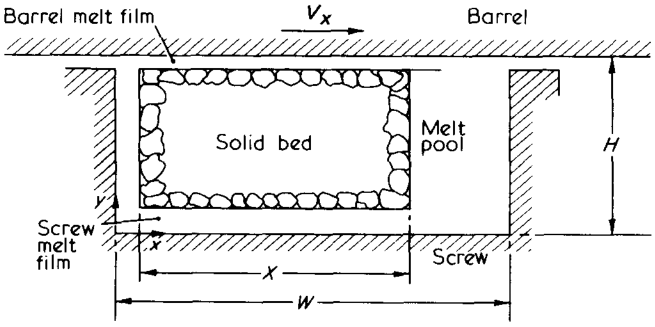

Figure 1 The melting mechanism

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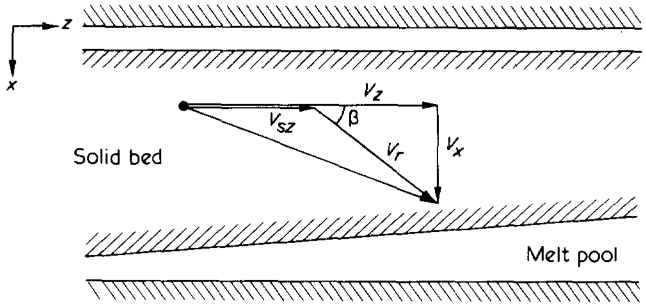


Figure 2 Relative velocity diagram for the solid bed

depth diminishes to negligible proportions. Very often, however, the process becomes unstable in the sense that the bed suffers breaks along planes apparently normal to the downstream direction. This phenomenon has become known as solid bed break-up. That it is a cause of surging has been established by the fact that subsequent pressure surging occurs at the same frequency[13], normally about five to ten times lower than that of screw rotation.

SOLID BED ACCELERATION

The reduction in solid bed width which normally occurs during melting can only be due to deformation of the bed, at least in the plane of the channel cross-section. But there is no reason why the deformation should be confined to this plane. The bed may be stretched in the downstream direction, an effect which would be detected as solid bed acceleration in this direction. Working from experimental observations, Donovan[15,16] suggested the existence of significant bed acceleration. Previously, all theoretical models of the melting process had assumed constant downstream bed velocity. Donovan proposed the use of a 'solid bed acceleration parameter' to allow the velocity to increase in a prescribed linear manner. Comparison of theoretical and experimental results showed that, while the velocity does vary, the form of variation cannot be readily prescribed.

Some later theoretical models of melting[13,17,18] relaxed the assumption of constant bed velocity and allowed the bed to deform freely in the downstream direction. The model used here is that described by Edmondson and Fenner[13].

In order to detect bed acceleration experimentally, it is necessary to measure bed velocity at several points along the screw. Two different techniques have been developed to do this. The first of these employs the pressure traces obtained from transducers mounted in the barrel wall at intervals along the screw. When a break in the solid bed passes a transducer, there is a significant change in the form of trace obtained from that associated with the presence of the bed to the profile due to melt alone[13]. Having passed a transducer, this same bed break will subsequently pass the next one. A measurement of the time elapsed between these two events allows the mean bed velocity between the transducer positions to be deduced. This technique is, of course, limited to a few velocity measurements after bed break-up has occurred. Its main use is in confirming the results of the second technique.

With some materials, notably polystyrene, distinctive markings can be seen on the surface of the polymer frozen in a screw channel after rapid cooling and screw extraction in experiments investigating the melting process. These markings take the form of parallel striations in the frozen melt film covering the solid bed, apparently caused by the motion of the barrel relative to the bed. The fact that the direction of these striations varies along the screw suggests a means of estimating solid bed velocities and accelerations. The angle, β, between the striations and the screw flight has been measured at a number of points along extracted screws in a range of experiments. *Figure 2* shows diagrammatically the various velocity components. V_z and V_x are, respectively, the downstream and transverse components of barrel velocity relative to the screw. Their resultant is V at an angle θ, the screw helix angle measured at the flight tips, to the downstream direction. If the solid bed moves downstream with velocity V_{sz} relative to the screw, the velocity of the barrel relative to the bed is V_r, as shown. The angle V_r makes with the flight is the one measured in the experiments. From *Figure 2* may be derived the result:

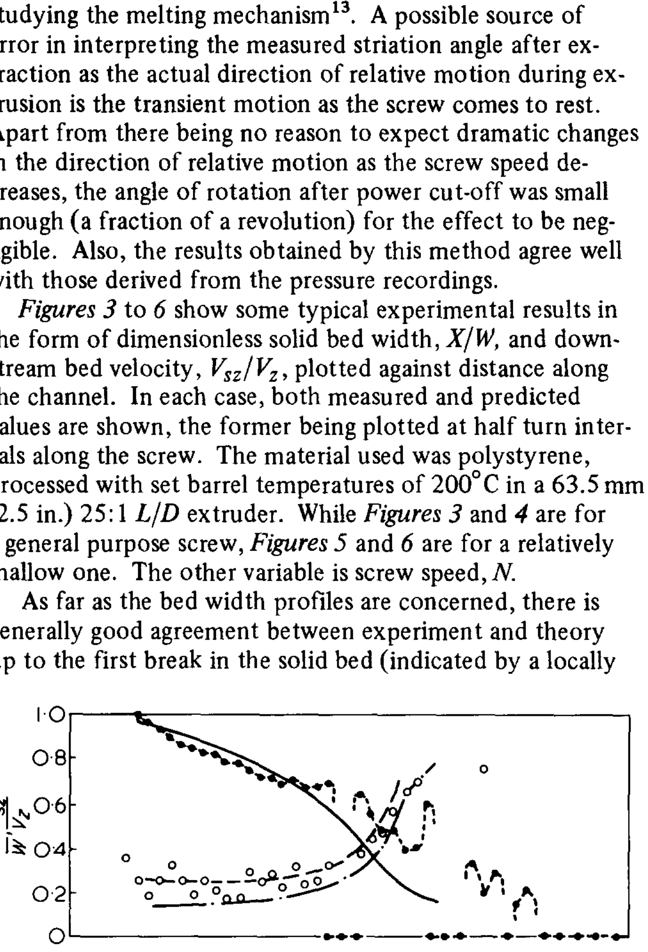
$$\frac{V_{sz}}{V_z} = 1 - \frac{\tan\theta}{\tan\beta}$$

which, since V_z, θ and β are known, allows V_{sz} to be calculated for positions at which β is measured.

The clarity of the striations in the particular experiments reported was due both to the translucent nature of the polystyrene used, and the tumbling of the granular feedstock with small quantities (50 ppm by wt) of carbon black powder prior to extrusion. The main purpose of this additive was originally to help distinguish intergranular boundaries in studying the melting mechanism[13]. A possible source of error in interpreting the measured striation angle after extraction as the actual direction of relative motion during extrusion is the transient motion as the screw comes to rest. Apart from there being no reason to expect dramatic changes in the direction of relative motion as the screw speed decreases, the angle of rotation after power cut-off was small enough (a fraction of a revolution) for the effect to be negligible. Also, the results obtained by this method agree well with those derived from the pressure recordings.

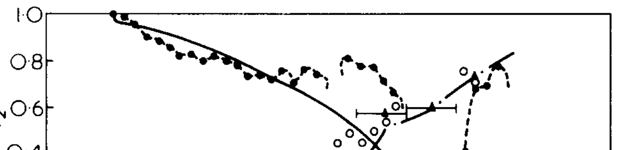
Figures 3 to *6* show some typical experimental results in the form of dimensionless solid bed width, X/W, and downstream bed velocity, V_{sz}/V_z, plotted against distance along the channel. In each case, both measured and predicted values are shown, the former being plotted at half turn intervals along the screw. The material used was polystyrene, processed with set barrel temperatures of 200°C in a 63.5 mm (2.5 in.) 25:1 L/D extruder. While *Figures 3* and *4* are for a general purpose screw, *Figures 5* and *6* are for a relatively shallow one. The other variable is screw speed, N.

As far as the bed width profiles are concerned, there is generally good agreement between experiment and theory up to the first break in the solid bed (indicated by a locally



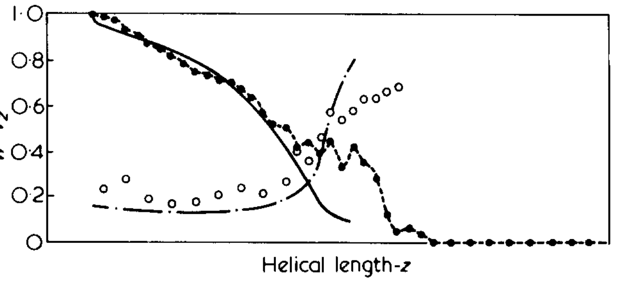
Feed (H = 9.91 mm)/Compression/Metering (H = 3.30 mm)

Figure 3 Experimental results for general purpose screw running at N = 60 rev/min X/W: — — ● — — ● —, experimental; ——, predicted. V_{sz}/V_z: ○, experimental from angle β; — ● —, predicted ρ_s = 1050 kg/m^3; — — —, predicted ρ_s = 610 kg/m^3



Feed (H = 9.91 mm)/Compression/Metering (H = 3.30 mm)

Figure 4 Experimental results for general purpose screw running at N = 90 rev/min. X/W: — ● — ● —, experimental; ——, predicted. V_{sz}/V_z: ▲, experimental from pressure profiles; ○, experimental from angle β; ——, predicted



Feed (H = 8.38 mm)/Compression/Metering (H = 2.79 mm)

Figure 5 Experimental results for shallow screw running at N = 60 rev/min. X/W: — ● — ● —, experimental; ——, predicted. V_{sz}/V_z: ○, experimental from angle β; — · —, predicted

zero bed width). After this, the theoretical model is not strictly applicable. There is also remarkably close agreement in shape between the experimental and theoretical bed velocity profiles. Most of the experimental values were obtained from striation angle measurements, although *Figure 4* also shows three points derived from pressure recordings. Since these represent mean velocities over finite lengths of the screw, the points are plotted at the middle of these lengths, which are also indicated. Most of the theoretical bed velocity profiles were obtained using a solid bed density of ρ_s = 1050 kg/m^3, appropriate for solid polystyrene. *Figure 3*, however, also shows the predicted profile for ρ_s = 610 kg/m^3, appropriate for polystyrene granules in bulk, which is in better agreement with the experiments. (Similar improvements could be obtained in the other three cases.) These results serve two purposes. Firstly, to demonstrate that the theoretical model correctly predicts solid bed acceleration, and secondly to provide the basis of a criterion for bed break-up.

CRITERION FOR SOLID BED BREAK-UP

The initial break-up of the solid bed during melting in an extruder is presumably due to some property of the local state of stress acting on the bed. A simple approach in the search for a suitable criterion might be to look for tensile stresses being created. This proves to be unprofitable owing to the high direct compressive stresses associated with the pressure in the melt surrounding the bed. A failure mechanism which involves internal shearing of the bed is more likely to be applicable. Unfortunately, a realistic analysis of internal states of stress and strain has yet to be performed, although Lovegrove[19] has made a start on the problem in the context of solids feeding.

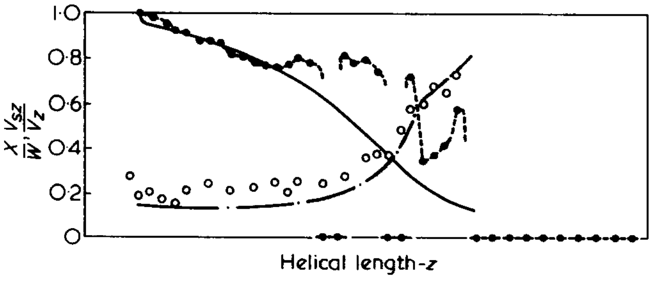
An alternative and more empirical approach is to use a criterion based on effects observed in the experimental results. For example, *Figures 3* and *4* show that solid bed break-up first occurs when the bed starts to show a significant increase in velocity, which must be associated with tensile deformation in the downstream direction. *Figures 5* and *6* for the shallower screw show less good correlation. While no complete break in the bed was obtained at 60 rev/min (*Figure 5*), the bed width became irregular in the region of high acceleration, an effect which might be described as partial breakage. At 100 rev/min (*Figure 6*), however, the first break occurs before significant increase in bed velocity. Further investigation of the experimental data suggests that bed break-up is also influenced by the pressure profile along the screw, and tends to occur close to a region of relatively low positive pressure gradient. This is not particularly useful for predicting instability, owing to the inability of the present theoretical model to predict pressure gradients accurately.

It should be borne in mind, with all the experimental results, that the true position of first break is not necessarily obtained. As the bed breaks intermittently, the instant at which the screw is stopped may be anywhere in time between successive breaks. Hence, the initial continuous part of the bed may be seen to extend beyond the position at which the next break will occur.

Although this solid bed acceleration criterion for break-up is far from perfect, it appears to be the most practically useful one at present available. In summary, bed break-up is likely to occur within one or two turns of the position at which predicted solid bed velocity first starts to increase significantly. If such an instability does occur, it will tend to cause surging.

AVOIDING BED BREAK-UP AND SURGING

As bed break-up and consequent surging occur only after the onset of increasing solid bed velocity, the instability can be reduced or eliminated by restricting this acceleration. It can be shown both experimentally and theoretically[13] that no significant bed acceleration occurs in the absence of a melt film between the bed and screw. In the presence of this film, whose thickness tends to increase progressively as freshly melted material is entrained, the shear stresses there which tend to restrain downstream motion of the bed are progressively decreased in magnitude. One way to prevent or delay the formation of the screw melt film, and hence prevent bed break-up, is to cool the screw[13]. Maddock[1] also demonstrated the benefits of screw cooling in reducing surging, but was not



Feed (H = 8.38 mm)/Compression/Metering (H = 2.79 mm)

Figure 6 Experimental results for shallow screw running at N = 100 rev/min. X/W: — ● — ● —, experimental; ——, predicted. V_{sz}/V_z: ○, experimental from angle β; — · —, predicted able to explain why. Unfortuantely, screw cooling has a detrimental effect on output rate but may be necessary if steadiness of output is the main criterion of quality.

In terms of screw design, it is clearly desirable to analyse a prospective screw geometry with the aid of a theoretical melting model of the present type to establish whether high solid bed acceleration is likely. There are various geometric and operating parameters such as compression section length and taper, barrel and screw temperatures and screw speed which can be altered to improve extruder stability. These effects are currently being studied. The extent to which bed break-up leads to surging detectable in the extrudate depends on the position of the first break, the length and depth of the metering section of the screw, and the downstream pressure profile there.

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