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Ultrasonic diagnosis of the single screw behavior during extrusion – a case study

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ABSTRACT

Ultrasonic diagnostic method of screw behavior during extrusion has been designed, developed and carried out on a 63.5-mm FLAG single screw extruder, equipped with either a barrier or Dry mixing screw. It was found that the screw behavior depends on the screw speed and die pressure. Whereas initially at low speed the screw centered by the hydrodynamic forces rotates smoothly in the axial position, at higher screw speeds and high die pressures the screw starts vibrating. Thus, (1) the screw tip vibrated with the amplitude of 10 – 210 μm as the screw speed varied from 5 to 100 revolutions per minute; (2) the screw vibrations in vertical and horizontal directions were asymmetrical; (3) the vibration pattern repeated itself at every two revolutions; (4) the vibrations originated in the poorly aligned engagement in the gearbox sleeve when the screw was pushed deeply into it by backpressure; (5) once pushed in the screw oscillated at any screw speed or die pressure.

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INTRODUCTION

"The extruder is indisputably the most important piece of machinery in the polymer processing industry".[1] The single-screw extruder (SSE) has been used in the 18-th century in Italy for the manufacture of pasta, and a century later in England for the production of soap (the machine was descriptively named as "plodder").[2] Adaptation of these devices to the plastics industry involved a progressive increase of the length-to-diameter ratio (L/D) from the original value of about 6 to ≤ 100. The demand that extruders perform multiple and diverse tasks, required not only increasing L/D, but also modification of the screw design from the original Archimedean type to a great variety that exists today. [1] Indeed, the screw design is one of the most important elements in any polymer extrusion process development and has been the focus of extensive theoretical, experimental, and simulation studies.[3] However, the dynamic mechanical behavior of the screw shaft itself during extrusion does not draw much attention, although it is widely accepted that a misaligned screw could be harmful not only to the product quality but also to the extruder itself; hence it has serious financial consequences.

Screw misalignment may originate in a number of sources, starting from poor machine design, progressive wear of the drive train, or even in the way the machine is being used. For example, counter-rotating twin-screw extruders (TSE) are known to be prone to screw wear by rubbing against the barrel wall caused by the calendering action between the screws. Considering the importance of the wear it is surprising how little attention is being paid to it in the plastics processing literature. Tadmor and Gogos in their basic text on polymer processing dedicated one page to the four types of wear (adhesive, abrasive, corrosive and surface fatigue). [4] Rauwendaal in his ever popular book on extrusion is brief on the subject. [1] Accordingly, wear by increasing the clearance between barrel and screw flights reduces effectiveness of the machine, viz. its melting and pumping capacity, the heat transfer, thus increasing non-uniformity of temperature. The recommended method for assessing the wear is disassembling the extruder and measuring the barrel diameter and screw dimensions. These measures might indicate the wear mechanism and suggest solution to the problem, usually based on plating, facing with hard alloys or replacing the screw and barrel.

To a great extent, the sparseness of the information about the dynamic screw behavior is caused by the lack of easy method for monitoring the screw behavior during the extrusion process and its wear. Ultrasound as a diagnostic tool has had countless successes in medicine and industrial non-destructive testing. The method is robust, fast, non-destructive, non-invasive, and cost-effective. The application of ultrasound to in-line monitoring of screw status and barrel wear during polymer extrusion processes has been developed at NRCC-IMI since 2002. For example, Jen *et al.* described the use of ultrasonics for the monitoring of TSE performance. [5, 6] The authors used a traditional stand-alone ultrasound sensor as well as a newly developed paint-on high temperature ultrasonic one for demonstrating the feasibility of measuring extruder barrel and screw wear. In that study, the rotation of a screw inside a TSE was observed by the ultrasonic sensors mounted on the outer surface of the extruder barrel. The monitoring was carried out for different TSE zones (melting, mixing and pumping) using four types of ultrasonic sensors with a fast data acquisition system. The TSE barrel thickness and the clearance between barrel and screw flights were measured during polyethylene (PE) extrusion in 30 and 50 mm extruders. The study has demonstrated the ability of ultrasonic sensors to monitoring the barrel thickness with precision of $\pm$ 27 μm and screw-barrel gap with that of 18 μm. The gap size in the co-rotating TSE was found to vary periodically from ca. 200 to 600 μm, indicating large screw vibrations within the partially filled machines.

However, to the present authors' knowledge, there has been no published study on the use of ultrasonic methods for the diagnosis of a SSE screw behavior under processing conditions. Thus, in the current study, the ultrasound technology described in ref. 5 and 6 was farther advanced by implementing a simultaneous 4-point sensing configuration. With the help of this configuration the screw behavior of a 63.5-mm FLAG SSE was studied under diverse processing conditions. The monitoring of screw status consisted of measuring the time of flight (TOF) for an ultrasound signal to travel from an ultrasound transducer to the screw flight and back, τ. The barrel-to-screw distance is given by: $d = V \times \tau / 2$, where V is the known value of the ultrasound velocity in molten polymer. The objective of this work was to answer questions whether and how much a screw tip vibrates, and how the screw speed and melt pressure at the die affect the screw behavior.

EXPERIMENTAL SETUP

Four ultrasound transducers (UT) were mounted in the terminal zone of the barrel of a 63.5 mm FLAG single screw extruder in 90° intervals, orthogonally to the screw surface (see Figure 1). Each UT continuously sends 5-MHz diagnostic ultrasonic pulses to the screw at a rate ranging from 600 to 700 pulses per screw revolution and keeps capturing the echoes reflected by the rotating screw. Every pulse wave is reflected back and forth several times between the UT and screw before completely dying out. The time delay between two consecutive echoes is the round-trip time of flight (TOF) of ultrasound signal from the UT to the screw. By measuring this time τ and by knowing the sound speed V in the polymer, the gap between the UT and the screw can be obtained.

Screw vibration can result in transient change of d, which in turn changes τ. Consequently, by measuring the variation of τ, the extent of screw vibration can be determined. The four UTs were synchronized in such a way that the movement of the screw was inspected simultaneously by them all. The melt pressure, P, and temperature, T, in the die zone were measured using a Dynisco melt pressure/temperature sensor. The P, T, and ultrasound signals were acquired with a PC-based high speed ultrasound system, custom-designed and built in the laboratory.[5,6]

Two types of screws were tested: a single flight barrier screw (#1); and a Dry-screw with a double flight mixing element in the terminal zone (#2). A polypropylene (PP) was extruded during the tests.

RESULTS AND DISCUSSIONS

In this study echoes reflected from the tip of screw flight were of interest. As shown in Figure 2, the position and length of the signal acquisition window was adjusted in such a way that only the first two echoes reflected from screw flight tip were recorded. For the single flight barrier screw #1, each UT only saw once the flight passing by during one screw revolution.

Figure 3 shows an echo graphic image of screw #1 acquired at UT_{upper} location (see Figure 1). The recording was made as the first test, starting at low screw rotation speed of 5 RPM, which generated die pressure of $P \approx 16.5$ MPa (2390 psi). In the Figure, a total of 12,250 ultrasonic echo signals are displayed from left to right on the horizontal axis (denoted as Nb acquisition) as recorded. The vertical strips are the intensities or amplitudes of the 1st and 2nd ultrasonic echoes reflected from the screw flight tip when it passes in front of the UT. The count of the flight tip echoes indicates recording for 20 screw revolutions. It is noteworthy that the acquired signals are in digital format. Each digital signal is composed of a series of numbers arranged in the same order as generated during digitization of the original analog signal. The vertical axis in the figure represents the sequence of sample points constituting each digitized signal. Since the sampling frequency was 250 MHz, the time elapsed between two sampled points was $t_s = 4$ nanoseconds. Thus, the length of each vertical strip in Figure 3 represents the duration of the corresponding echo signal. For a strip of 50 units long on the vertical axis, the duration of the corresponding echo signal is: $50 \times 4\ ns = 200\ ns$. The starting point of each strip is a function of flight-to-UT distance and the ultrasound velocity in the polymer. In Figure 3 the line labeled as "Arrival line" indicates arrival positions of the 1st echo recorded during the screw rotation. In this run, the screw rotation was stable; the measurements carried out at other three UT locations showed the same screw rotation stability within the experimental error of about $\pm 10\ \mu$m.

Figure 4 shows the second test of the series as the echo signal reflected from screw #1 at 20 RPM. The die pressure was $P = 27$ MPa (3930 psi). The recording covered 17 screw revolutions. In this Figure as well as in Figures 6, 7, and 8, two lines labeled as "Arrival lines" indicate respectively the earliest and the latest arrival positions of the 1st echo recorded during the screw rotation. The distance between these two lines might be converted into distance as:

$$\Delta = V \times (N \times t_s) / 2 \qquad (1)$$

where N is the number of units on the vertical axis between the two lines in the Figure. A denominator 2 is used because the echo travelled twice the distance between the screw flight and the UT. The value of Δ can be used as a measure of screw radial oscillation during the period the echographic image was recorded. In this case, small radial screw oscillations are evident at all four UT locations, with the largest deflections observed by the left and lower UTs. The screw oscillation pattern repeated itself at every second revolution. The oscillation pattern was stable at three of the four UT locations, except that at the right UT location where a transition to small oscillation was observed. Evidently, the oscillatory behavior of the screw was not radially symmetrical.

The experimental results indicate that at the same screw speed, *T* and *P* the screw behavior is not necessarily the same, as the past screw speed and *P* affect it as well. This is demonstrated in Figure 5, where the magnitude of screw tip radial movement is plotted vs. the screw speed. For example, in one test series, the extrusion started at 5 RPM with the die exit fully open. Then the die gap was reduced and the screw speed increased to 20, 50 and 100 RPM. After that, the screw speed was reduced back to 5 RPM. Table 1 shows the test results for this series. The radial oscillation, denoted as Δ, was measured at the left UT location. The variation of Δ versus logarithm of pressure (P) is displayed in the Figure 5 with the linear regression line for tests # 1 to 5. For the 1st five tests, Δ linearly increases with log(*P*), suggesting a gradual engagement of the screw into the gearbox sleeve at increasing die backpressure. Consequently, the test #6 shows a different behavior – the screw oscillation is noticeably larger than what might be expected for 5 RPM and P = 8.1 MPa. The reason could well be that once the screw is pushed into the gearbox sleeve, it does not return to its initial axial position when the die backpressure is reduced. Thus, it seems that the origin of screw vibration is related to some misalignment of the sleeve or the gearbox itself.

Table 2 lists the tests results performed at 5 RPM under different processing conditions (*e.g.*, different die gap, tests in different days, at the start of a test series or after some tests at higher screw speed). Here, the data do not suggest any correlation between Δ and *P*.

The conjecture that the screw deviation is rather dictated by the screw engagement into the gearbox (and possibly its condition) than the melt pressure and RPM is further confirmed by the result of the following tests. Here, the extruder was run steadily at 5 RPM with P = 16 MPa (2320 psi) at the die. Next, the speed was increased to 20 RPM, thus increasing the die pressure to P = 26 MPa (3780 psi). For the initial 1 to 2 minutes the screw remained stable, and then started to oscillate, suggesting that the screw was engaged further in the gearbox under higher backpressure (see Figure 6). Five minutes later, the feeder was stopped and during the following 9 min the melt pressure gradually dropped to stable P = 12.4 MPa (1800 psi) for the remaining 4 min of the test (there was almost no more extrudate coming out of the die exit). Figure 6 displays echo signals recorded at about 1, 2, 3, and 18 minutes into the test. It is evident that for the initial one min the screw rotated without oscillation, then the amplitude of oscillation gradually increased to about 100 μm. Once the screw was engaged in a final position the deviation remained constant regardless of the subsequent die pressure indicating that screw deflection is related to the axial screw position.

In another series of tests, the extrusion started at 100 RPM. Then the screw speed was reduced sequentially to 50, 20, and 5 RPM. Figure 7 displays the transitional behavior of screw oscillation during the first couple of minutes after starting the extruder at 100 RPM. In Figure 7(a) the oscillation at left UT location started at 177 μm and increased slowly. In Figure 7(b) at the right UT location the oscillation started at 115 μm and decreased much faster. Incidentally, the disparity of screw behaviors observed at left and right UT locations in this run is quite similar to that observed in Figure 4(c) and (d). Three minutes later, the oscillations at the left (Figure 7(c)) and right (Figure 7(d)) UT locations stabilized at 209 μm and 30 μm, respectively. The significant difference in the oscillation magnitude at the two locations indicates that the screw movement was heavily asymmetrical even though the oscillation was taking place in a steady manner, as shown in Figures 7(c) and (d). Table 3 lists the screw deviation measured at the four screw speeds after the screw vibration stabilized. For this particular test series, the screw behavior at 50 and 20 RPM were quite similar despite the reduced screw speed and P. The oscillation at 5 RPM was well balanced (about the same at two UT locations), more so than at higher screw speeds. This may suggest that more consistent product quality could be expected at this screw speed. The results suggest that, at least for this test series, a decrease in screw oscillation at the left UT location was accompanied by an increase in screw oscillation at the right UT location. However, this observation should not be generalized.

Similar tests were also performed using the Dry mixing screw #2. Figure 8 displays the echo signals at 5 RPM for about 20 screw revolutions. The die pressure was $P \approx 24$ MPa (3470 psi). Since the probed screw zone had double flights, for every one screw revolution, each UT saw twice a flight passing by, thus the number of echo appearance doubles in comparison to the records shown for screw #1. Evidently, the screw vibration pattern repeats itself at every 2 revolutions, confirming that the screw oscillation does not originate in the screw, but rather in the way it is mounted into the screw gearbox.

It is noteworthy that for SSE with a single-flight screw rotating at constant speed any UT sees the screw flight passing by at two distances, *e.g.*, all even-numbered echoes are close to UT thus to the barrel wall, and all odd-numbered echoes further away. Consequently, the misaligned screw does not rotate with a constant angle from the extruder barrel axis, but rather vibrates like a dumped elastic rod. The deviation from the hydrodynamically favored axial rotating position results in unbalanced radial pressure at the screw end – high normal pressure where the screw-barrel gap is small, and low pressure where it is large. The data from the four radially located UT demonstrated that the vibrations are not fully symmetrical, as the misalignment angle imposes a bias.

CONCLUSIONS

Ultrasonic diagnosis of the dynamic behavior of a barrier and a Dry screw during extrusion has been carried out for a 63.5 mm (2.5") FLAG single screw extruder. The results demonstrated that the manually inserted screws at low backpressure smoothly rotate at the axial position. However, once the die pressure increases above about 7 MPa, the screw tip starts oscillating, with amplitude increasing with the backpressure. Since the subsequent reduction of pressure does not result in a smooth central rotation, it has been postulated that the origin of this behavior is the misalignment of the screw mounting in the gearbox sleeve – once the screw is deeply pushed by the die pressure it stay there independently of the pressure reduction. The ultrasonic approach discussed in this work is a valuable tool for the quality control of the installation and the well-being of an extruder screw and the mechanics it is associated with. The developed setup of four ultrasonic transducers opens the possibility of simultaneous, *in situ* measurements of the screw-barrel gap and its stability. Furthermore, the setup is capable of providing information about the limits of safe operation, *i.e.,* the maximum screw speed and the die pressure. In addition, with the four transducers the wear of the screw flights might be continuously monitored.

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TABLES

TABLE 1. Results of the one test series listed in a sequential order of the tests

Test #	Screw speed (RPM)	Melt pressure (psi)	Melt pressure (MPa)	Δ at left UT location (μm)
1	5	350	2.4	0*
2	20	770	5.3	64
3	20	2350	16.2	113
4	50	2950	20.3	146
5	100	3750	25.9	147
6	5	1170	8.1	130

*: 0 represents the case where screw deviation was not noticeable.

TABLE 2. Results of tests carried out at 5 RPM (in historical order)*

Melt pressure (psi)	Melt pressure (MPa)	Δ at left UT (μ m)
350	2.4	0
1170	8.1	130
2580	17.8	160
2250	15.5	139
2400	16.6	0
2360	16.3	19
2390	16.5	0
1100	7.6	0

*: 0 represents cases where screw deviation was not noticeable.

TABLE 3. Test results at four screw speeds (in sequential order)

Screw speed (RPM)	Melt pressure (psi)	Melt pressure (MPa)	Δ at left UT (μm)	Δ at right UT (μm)
100	5700	39.3	209	30
50	4750	32.8	161	129
20	3700	25.5	169	126
5	2250	15.5	139	138

FIGURE CAPTIONS

Figure 1. Four ultrasound transducers (UT) flush-mounted in the terminal zone of the extruder barrel, perpendicularly to its surface. Each UT sends ultrasonic pulses and captures the echoes reflected from the screw. The time delay τ between two consecutive echoes (right) is the round-trip travel time between the UT and the screw.

Figure 2. Depending on screw position (left), echo signals reflected from the screw flight tip appear in the signal acquisition window once per single screw rotation (right).

Figure 3. Echo signals reflected by screw #1 at 5 RPM and received by the upper UT. The melt pressure and temperature was ca. 16.5 MPa (2390 psi) and 200 ºC, respectively.

Figure 4. Echo signals reflected by screw #1 at 20 RPM and received by the upper (a), lower (b), left (c) and right (d) UTs. The melt pressure and temperature were ca. 27 MPa (3930 psi) and 200 ºC, respectively.

Figure 5. Plot of the screw #1 deviation Δ versus common logarithm of P (data in Table 1). The deviation was measured at the left UT location. The numerals in the Figure indicate the sequence of the tests. The linear regression was made for tests #1 – 5.

Figure 6. Test records at about 1 (a), 2 (b), 3 (c), and 18 (d) minutes into a test carried out at 20 RPM and received by the right UT. For (a), (b), and (c), the die pressure was 26 MPa (3780 psi) and for (d) it was 12.4 MPa.

Figure 7. Echo signals reflected by screw #1 at 100 RPM and received by the left (a, c) and right (b, d) UTs at the beginning of the test and 3 minutes after. The melt pressure and temperature were ca. 39.3 MPa (5700 psi) and 200 ºC, respectively.

Figure 8. Echo signals reflected by the Dry screw #2 at 5 RPM and received by the upper (a), lower (b), left (c) and right (d) UTs. The melt pressure and temperature was around 24 MPa (3470 psi) and 200 ºC, respectively.

FIGURES

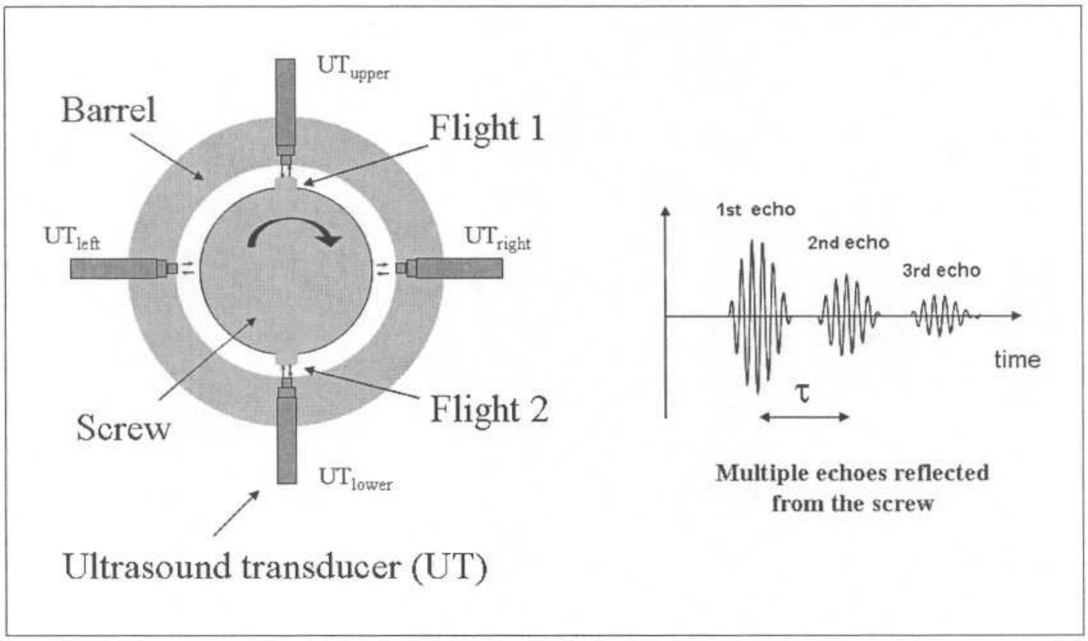
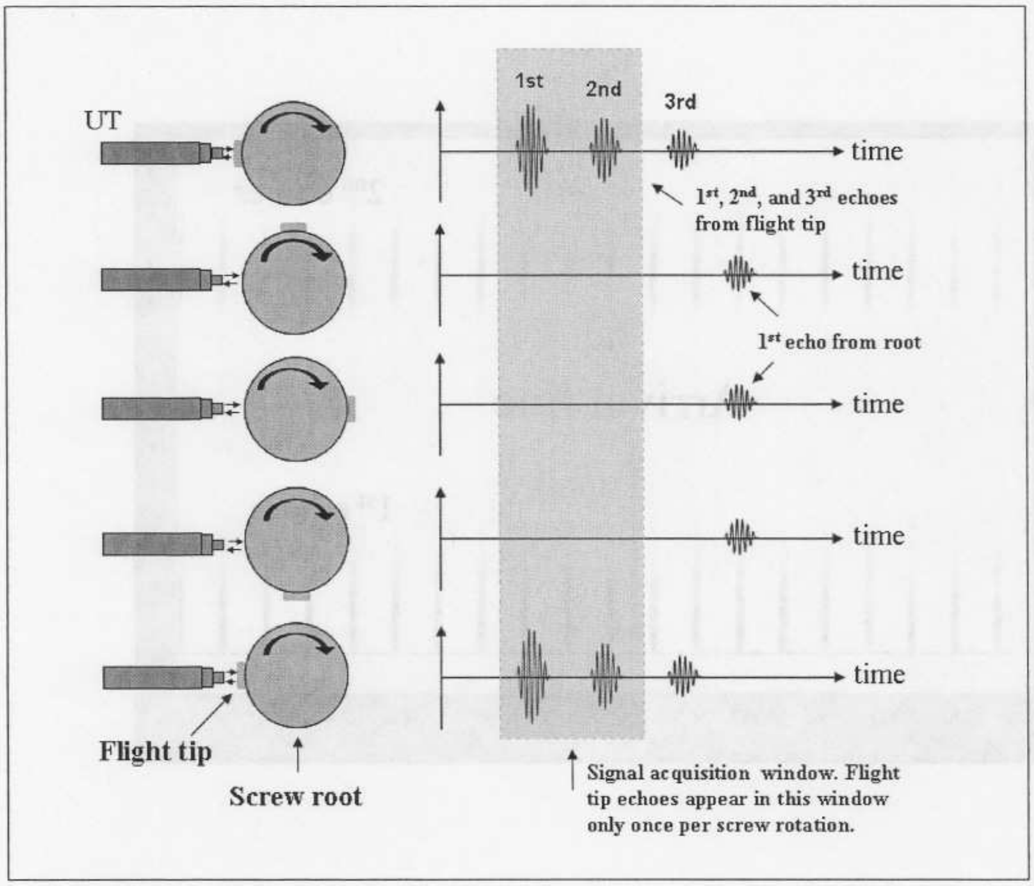


Figure 1.



UT
1st
2nd
3rd
time
1st, 2nd, and 3rd echoes from flight tip
time
1st echo from root
time
time
time
Flight tip
Screw root
Signal acquisition window. Flight tip echoes appear in this window only once per screw rotation.

Figure 2.

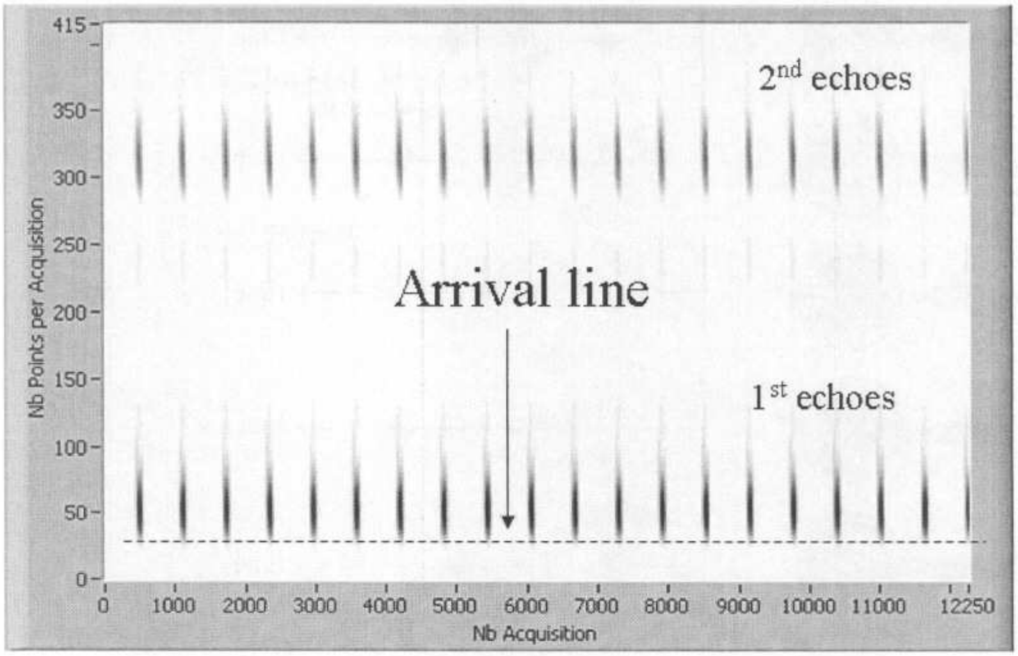

2nd echoes
Arrival line
1st echoes
Nb Points per Acquisition
Nb Acquisition
415
350
300
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12250

Figure 3.

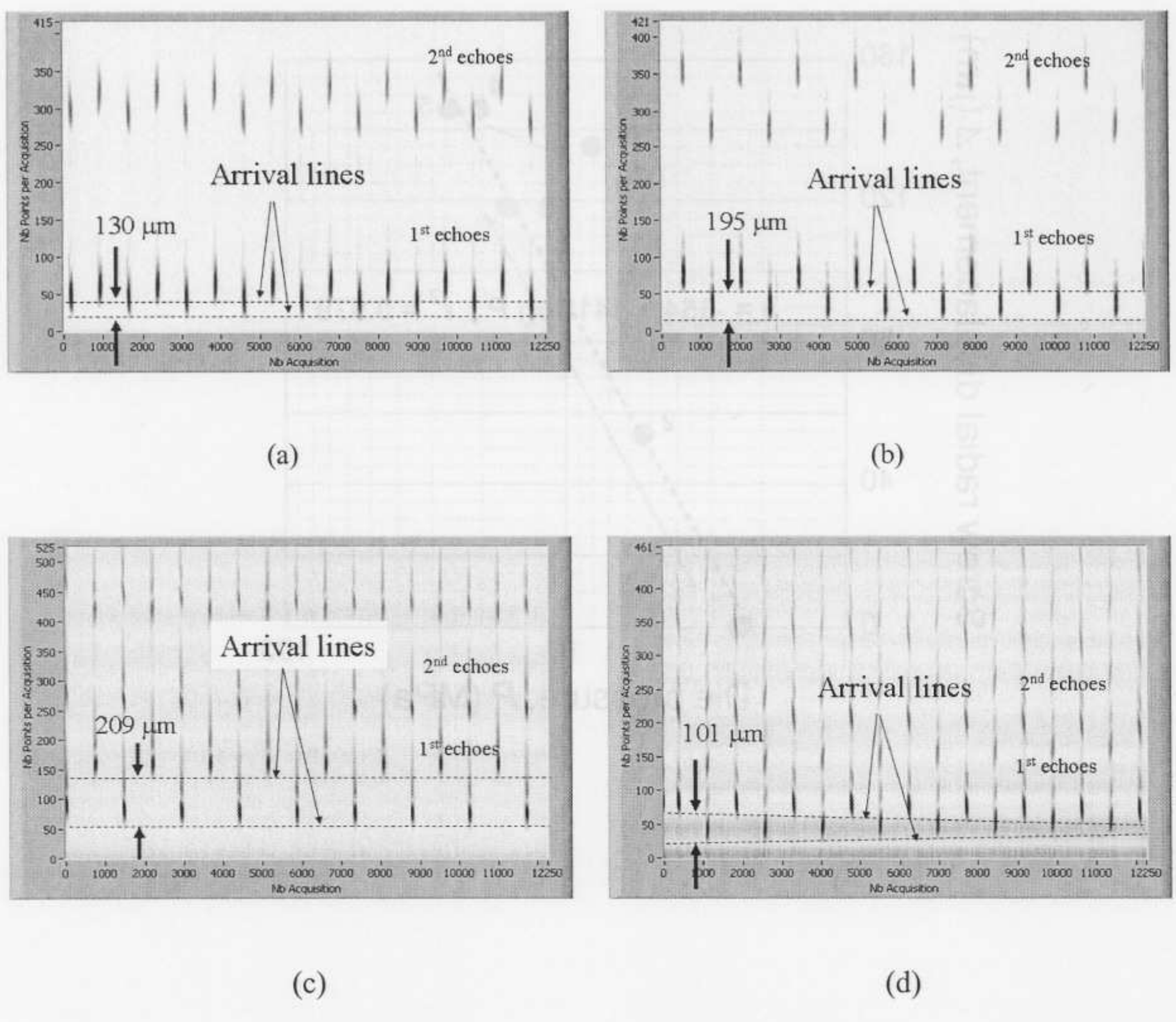
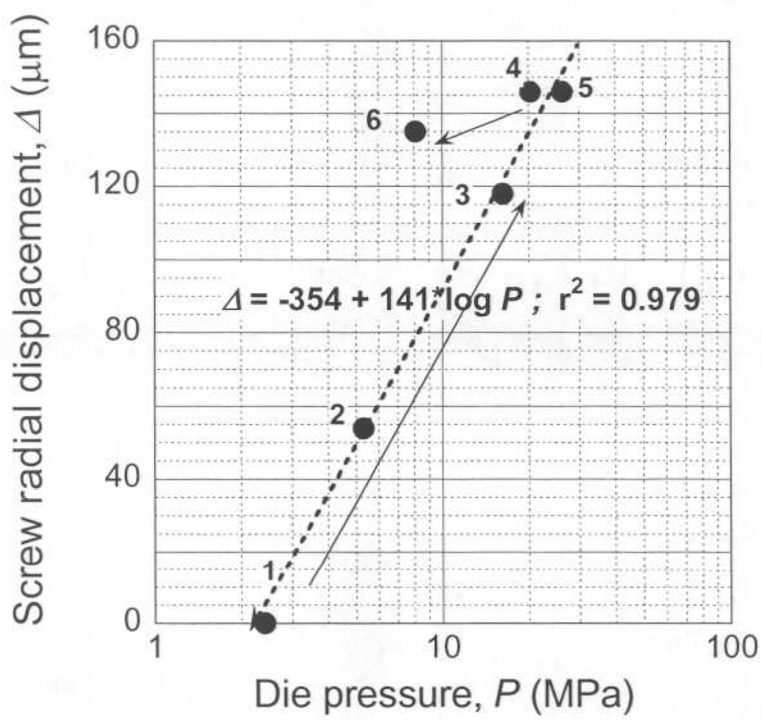

2nd echoes
Arrival lines
130 µm
1st echoes
Nb Points per Acquisition
Nb Acquisition
(a)
2nd echoes
Arrival lines
195 µm
1st echoes
(b)
Arrival lines
2nd echoes
209 µm
1st echoes
(c)
Arrival lines
2nd echoes
101 µm
1st echoes
(d)

Figure 4.



160
120
80
40
0
1
10
100
Screw radial displacement, Δ (μm)
Die pressure, P (MPa)
Δ = -354 + 141*log P ; r² = 0.979
1
2
3
4
5
6

Figure 5.

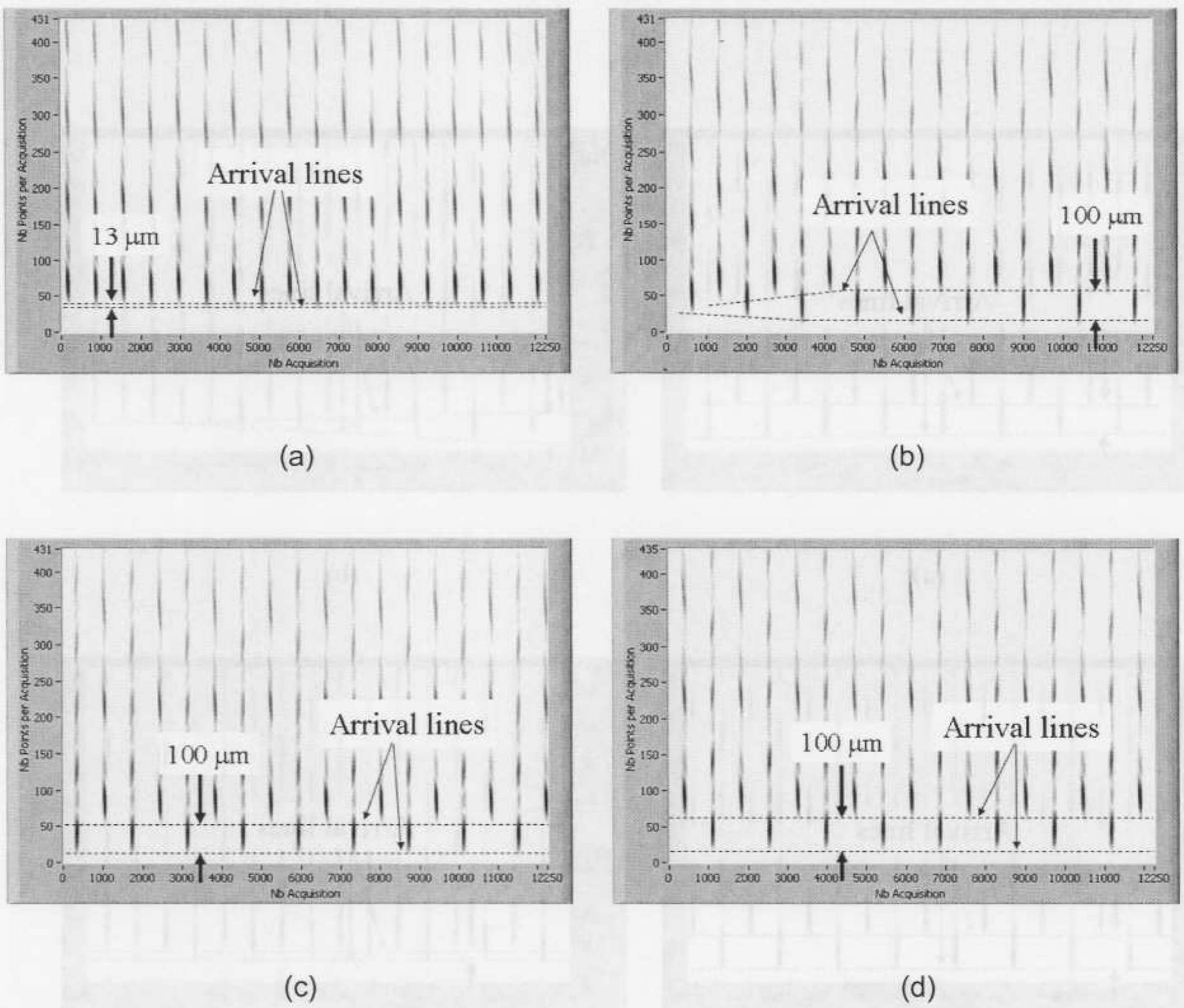
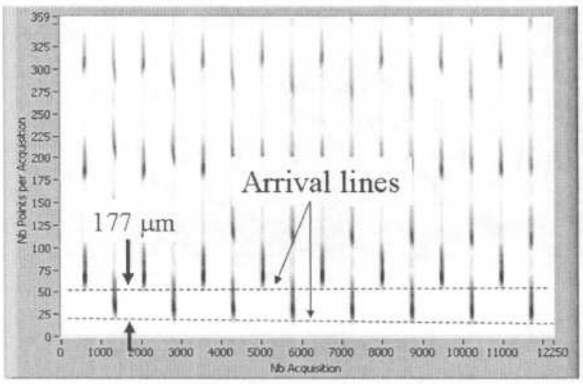
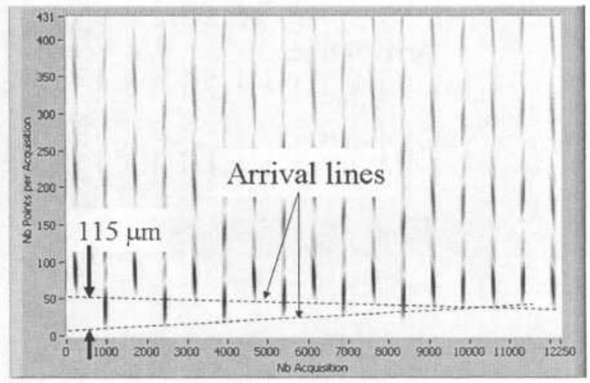

Arrival lines
13 μm
Arrival lines
100 μm
Arrival lines
100 μm
Arrival lines
100 μm
Nb Points per Acquisition
Nb Acquisition
(a)
(b)
(c)
(d)

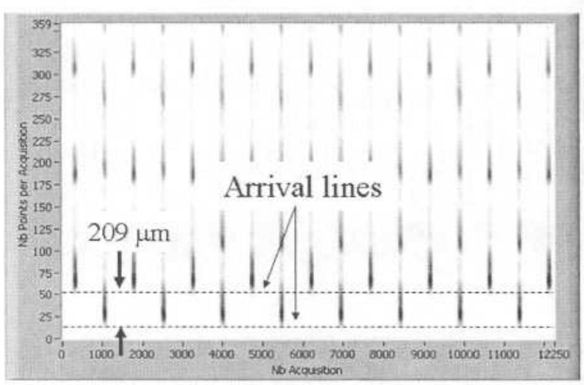
Figure 6.



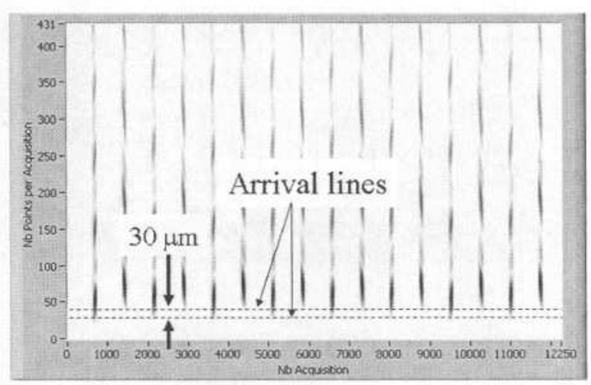
(a)



(b)



(c)



(d)

Figure 7.

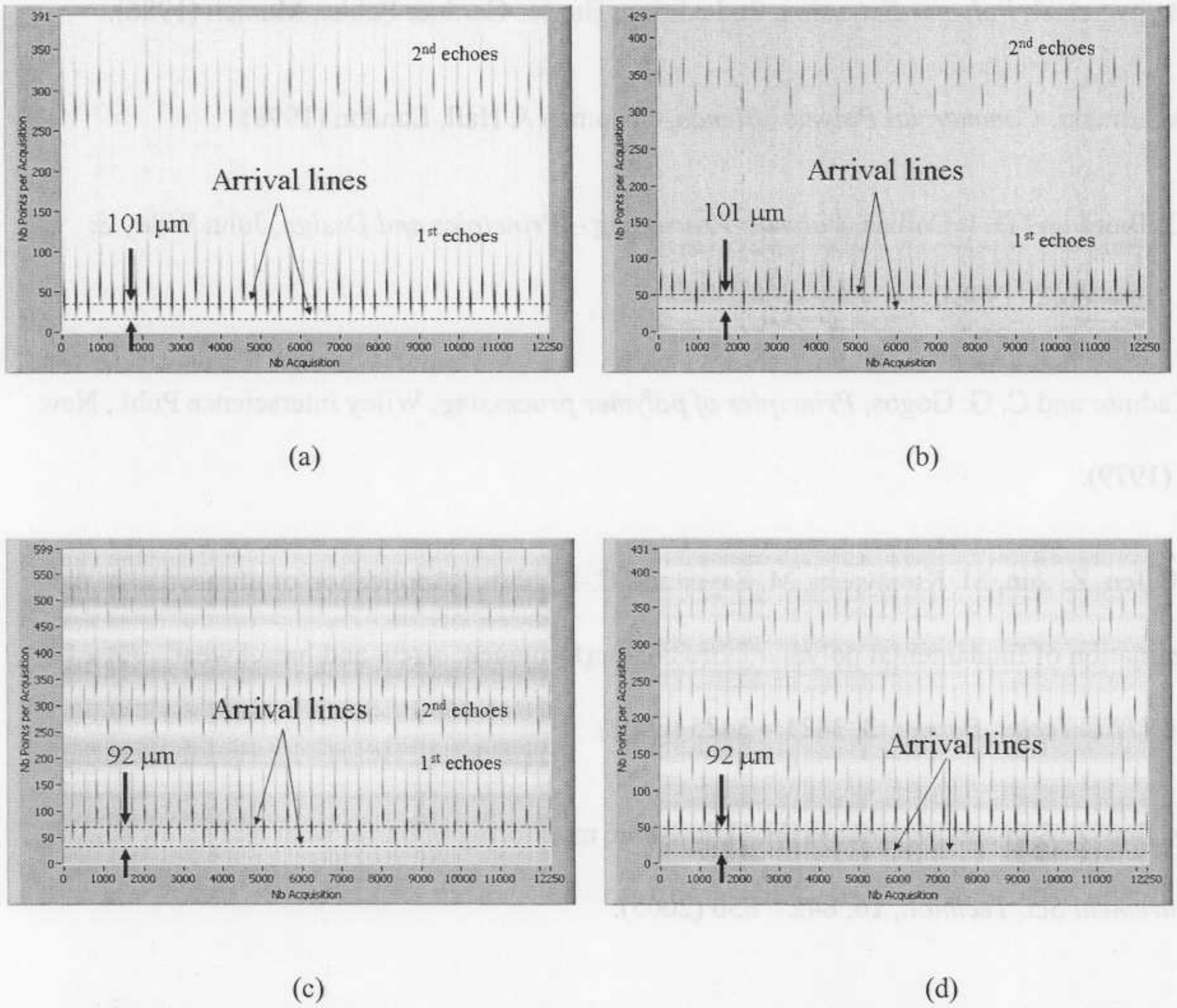

2nd echoes
Arrival lines
101 μm
1st echoes
Nb Points per Acquisition
Nb Acquisition
(a)
2nd echoes
Arrival lines
101 μm
1st echoes
Nb Points per Acquisition
Nb Acquisition
(b)
Arrival lines
2nd echoes
92 μm
1st echoes
Nb Points per Acquisition
Nb Acquisition
(c)
92 μm
Arrival lines
Nb Points per Acquisition
Nb Acquisition
(d)

Figure 8.

REFERENCES

[1] C. Rauwendaal, *Polymer Extrusion*, 2nd edition, Hanser Gardner Publs., Munich (1986).

[2] L. A. Utracki, *Commercial Polymer Blends*, Chapman & Hall, London (1998).

[3] D. G. Baird and D. I. Collias, *Polymer Processing – Principles and Design*, John Wiley & Sons, New York (1998).

[4] Z. Tadmor and C. G. Gogos, *Principles of polymer processing*, Wiley Interscience Publ., New York (1979).

[5] C.-K. Jen, Z. Sun, M. Kobayashi, M. Sayer and C.-K. Shih, "Application of ultrasound in the determination of fundamental polymer extrusion performance: screw and barrel wear", *Proc. SPE ANTEC Techn. Papers,* **3**, 3421 – 3425 (2002).

[6] C.-K. Jen, Z. Sun and M. Kobayashi, "Ultrasonic monitoring of barrel wear and screw status", *Measurement Sci. Technol.*, **16**, 842 – 850 (2005).

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