Single Screw Elongational Mixing Developments For Continuous Mixing Applications

by

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ACKNOWLEDGMENTS
AND
THANKS

The conceptual design of the novel mixing elements described in this paper was suggested by Mr. Bill Theile of American Leistritz. This paper, and the mixers it describes would not have been possible without him. His tutelage in mixing theory has been generous, patient, clear, and concise. To say only, “Bill, thank you,” seems entirely too little.

Any errors in the execution of his idea or the study that follows are entirely mine.

I) Abstract: A single screw extruder equipped with a novel elongational mixer made films made films comparing a 24/1 single screw extruder with a Union Carbide mixer and a Double Wave mixer. Materials processed include olefins with elastomer, polypropylene with color concentrates and flexible vinyl. The study shows the effects of elongational stress on mixing and melting performance. Sheet was also made from wood flour and LDPE pellets directly without any intermediary compounding.

II) Introduction: There are many single screw mixing devices and many claims are made for each one—often without any supporting experiments that clearly delineate advantages.

Laboratory extrusion machine builders have traditionally scaled down what was available in production including, Union Carbide, Double Wave, Dulmadge pin, Saxon, Egan, Eagle, and many others. Further, all the various static and active mixers are applicable to the lab environment. Fitting particular mixers into a lab tool has been only a matter of engineering and available funds.

Nevertheless, when these mixers are used in small extruders, they don't compound very well—even compared to larger single screw extruders.

Laboratory single screw compounders suffer from problems associated with being small. Lower shear rates, lower backflow, and the repercussions of using the same size pellets in laboratory extruders as in large extruders all reduce the mixing performance. This deserves some discussion.

Inherent Effects of Small Extruders: Historical

Shear rates for a 5/8 inch extruder are roughly one-third that of a 4.5 inch extruder. Many people regard higher shear rates as important to mixing.

Small screws having small channel depths are much better pumps than large extruders because of their small channel depths[1]. Therefore, there is little back mixing even at high pressures generation. So, large extruders are sometimes thought to be better mixers because they are poorer transporters.

Pellets, very often, are, "one size must fit all extruders." This becomes a significant problem when considering the small laboratory single screw compounder.

It is a truism that, the better mixed the material enters the extruder, the better mixed is the output. Consider a simple mixture of conventional nominal 1/8 inch pellets mixed with a 1% additive concentrate of the same size and weight. Next, think about how

[1] Tadmore and Klein, Engineering Principles of Plastic Extrusion, 1978, Robert E. Krieger Publishing Co. P221.

many standard 1/8 inch pellets there are in a 5/8 inch extruder compared with larger machines. A 5/8 inch 24/1 L/D screw may contain only 330 pellets or an average of 14 pellets per L/D. Just as the output of extruders goes up with the square of the diameter, so does the number of pellets.

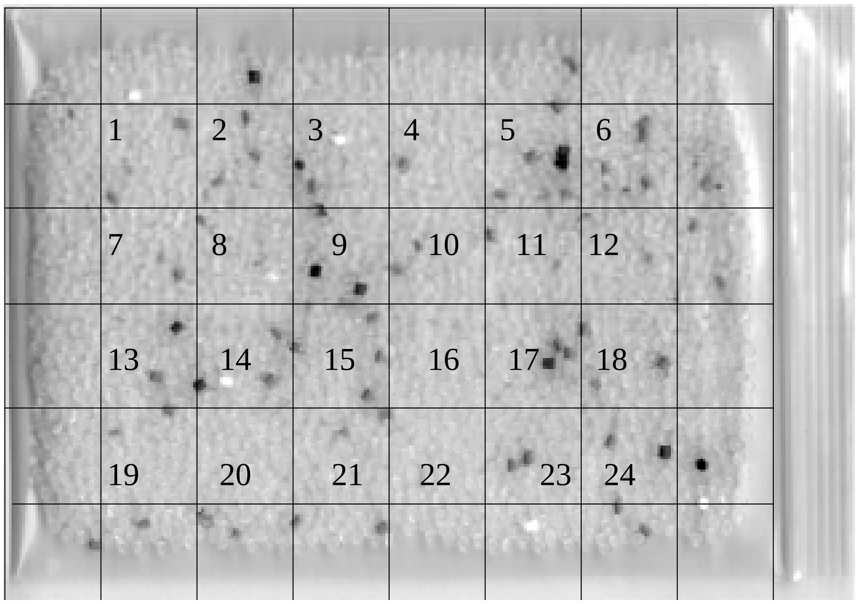
If we imagine a perfectly mixed 1% additive of the same pellet size, the 5/8 inch extruder will only have 3 pellets of the additive spread throughout 24 L/Ds! The extruder is required to mix one pellet into 8 L/Ds. Even a small 2 inch extruder sees a remarkable improvement in the quality of the incoming mixture as it will have 9 additive pellets in each L/D.

The problem is worse than this when you consider that the mixture is unlikely to be perfectly mixed. What are the odds that the additive will enter in a perfectly timed pattern? Awful. In our 3 pellet per 8 L/D example, it's very probable that only 2 or as many as 4 pellets could be in the extruder at one time. It doesn't stretch the limits of credibility to suggest that there will be times when only 1 pellet might enter. If the hopper mixture were slightly uneven, there might even be no additive pellets in the entire screw—a difficult mixing problem to be sure.

Consider the following example. Polypropylene is mixed with four colors of concentrate pellets in a large drum. The mixture is known to extrude satisfactorily in a large extruder. A small amount of the mixture was place in a zip lock bag, scanned, and a grid place over the bag. Each full grid contains about 64 pellets or about 4 L/D's of fill. Considering only the full 24 grids, we see a great deal of variation may enter any flight. Grids 3, 8 and 14 have a single white pellet. If we imagine that material was flowing into the extruder from grids 19 to 24, then not a single white pellet would be in the extruder! In a large extruder, this entire bag would fill one flight.

Polypropylene Mixture

Varying color concentrate in each grid enters small extruder.



Micro-pellets would seem to avoid these problems and some companies do use this option. Nevertheless, such pellets are expensive, inconvenient, and often require at least one additional processing history. Consequently, many people regard this option as unsatisfactory.

The Problems With Compression

Most single screw extruders are flood fed. That is, you fill the hopper and the screw channel fills to its limit. You compress the solids and melt them to fill the end of the screw. To make stable pumping extruders, this is often helpful.

However, compression of solids is not necessarily consistent with good mixing. Consider a compressive extruder where equal amounts of two types of pellets, A and B, are to be mixed in the extruder. On entering the screw, it is extremely unlikely that the mix will be perfect, i.e. A-B-A-B-A-B-A-B etc. Some inconsistent sequence will likely occur such as A-A-A-A-B-B-B-B. High compression of this sequence at high pressure often results in very sturdy “A” and “B” where each agglomeration has to be broken up, i.e., mixed by dispersion, and then mixed intimately with each other, i.e. by distribution. This is inherently counterproductive.

Compression of the components, therefore, takes the incoming mixture and makes the problem of mixing worse. Generally, the higher the compression or the sooner compression takes place along the screw and the worse the problem created. Starve feeding limits the compression before the mixing section. This is one of the reasons why starve fed twin screws are so successful.

So, wanting to make a better single screw compounder, we concluded that if flood feeding is to be used, compression before melting should be minimized. We also decided to investigate starve feeding as part of the study.

The Long Vertical Screw

The success of the vertically designed extruder improved the lab extruder itself. The natural advantages of better feeding and screw strength formed the basis for a better laboratory extruder.[2] A natural extension, literally, of this technology was to increase the L/D ratio dramatically. This is possible because the vertical screw is in tension rather than compression. This eliminates the buckling forces (caused by pressure at the tip of other screws) that otherwise destroy long small screws.

We decided that a 50:1 L/D 5/8 inch diameter screw would present a serious opportunity for additional mixing length without unnecessary sacrifice of strength.

Length is an important attribute of a screw for many reasons. Length presents the opportunity to begin the melting process without compression. Witness, for example, the figure 8 path of a co-rotating twin screw extruder. Roughly, the effective L/D is doubled because the material follows a longer pathway. The conventional starve fed mode allows energy input without compression. In turn, this allows high viscosity melts to enter mixing sections at the most opportune time. That is, *before* heat is generated in the melt and the viscosity is reduced.

Additional Theory

We were not satisfied with the mixing elements as used on lab extruders. White points out that, "… extensional and elongational flow are more effective in distributive mixing than shear flow."[3] Erwin argued that the reorientation of elements greatly reduced striation thickness.[4] Certain minimum stress levels were summarized by Rauwendaal as required for dispersive mixing.[5] Finally, Thiele[6] suggested that both distribution and dispersion might be possible in a single screw extruder by modifying a fluted mixer such as a Union Carbide mixer. He suggested that, *rather than concentrate on shear rate*[7], that opening the inlet channel of a typical Union Carbide fluted mixer could put the flow into extension to increase the *shear stress*; if we staged the mixing elements, as in twin screw extruders, we might further benefit by additional re-orientation.

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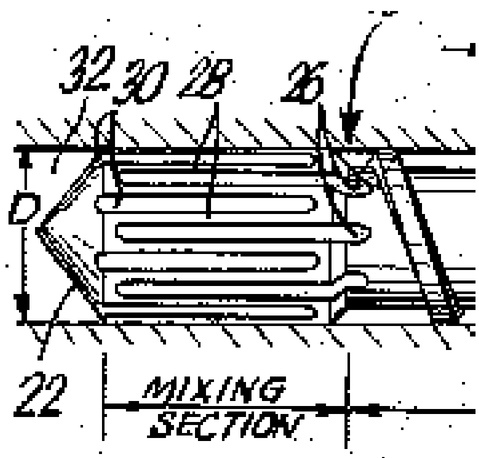
[2] Luker, Innovations In Extrusion Technology, web site publication at www.randcastle.com
[3] White, Twin Screw Extruders, Hanser Publishers, NY, 1990, p 42.
[4] Ibid, p 43.
[5] Rauwendaal, Extrusion Engineering, Hanser Pub., 1986, p 427.
[6] Private conversation, William Theile and Keith Luker about 1996.
[7] Rauwendaal, Extrusion Engineering, Hanser Pub., 1986, p 416.

Randcastle, therefore, undertook the construction of a 5/8 inch diameter 50:1 L/D with mixers that would employ elongational mixing. The novel mixers were called BT mixers after Bill Theile.

III) Relevant Prior Technology: Of the many mixing elements that have been made, three fluted mixers are of particular interest to this paper. They are popular and share similarities with the BT Mixer that is the subject of this paper. These are the Union Carbide[8], Egan[9], and the Dray[10] mixers. The Union Carbide and Egan mixers have closed inlet channels(#26 below). The Dray mixer does not.



Typical Union Carbide Mixer And Location

The Egan mixing section is similar to the Union Carbide mixer but the flutes are helical.

These mixers are often claimed to have dispersive mixing properties because, "In the barrier clearance the material is subjected to a high shear rate, the corresponding shear stress should be large enough to break down particles in the polymer melt".[11] Rauwendaal gives an analysis and design recommendations.[12] He concluded that,

> The most important design features for a fluted mixing section can be summarized as follows. The helix angle should be 50 to 60 degrees, the clearance should not be smaller than ½ mm (0.020 inch) and the axial length should not be less than two diameters. Further the number of inlet channels should be three or four. The chance of hold-up of material can

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[8] G. LeRoy, U.S. Patent 3,486,192
[9] R. B. Gregory and L. F. Street, U.S. Patent 3,411,179
[10] R. G. Dray, U.S. Patent 3,788,612.
[11] Rauwendaal, Extrusion Engineering, Hanser Pub., 1986, p 416.
[12] Ibid p 416-432.

be reduced by tapering the channel depth. The chance of hold-up can be further reduced by tapering the channel width.[13]

An important assumption in the analysis is that the mixer is filled with *plasticized material under compression.*

Unlike the other two mixers, the Dray mixer, shown below, has an open tapered inlet channel. Several variations are shown in the patent. The variation closest to the BT mixer is shown in Fig. 1 below. According to the patent,

> The material is then forced through flutes 14 under pressure of the feed from screw section 4. As the material proceeds along the flutes it undergoes increased resistance because of the progressive shallowing of flutes 14 from the inlet to the discharge end. Consequently, the material is forced out of the flutes 14 and onto the adjacent lands 26. As the plasticized material passes over the lands 26 it is subjected to shear forces which provides the required mixing.

In the preferred embodiment cited in the patent, it is suggested that, for a 6 inch screw, the mixing element should be 8 inches long.

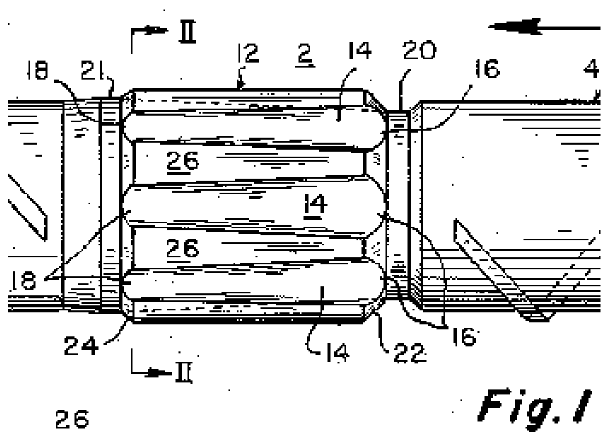


Fig. 1

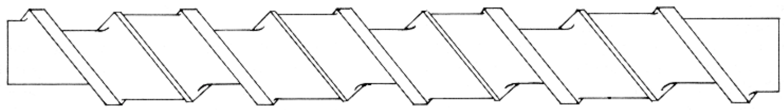
Importantly, there is no mention of preferred mixer location for any other embodiment. However, since the material is described as plasticized and forced through increasing resistance through the mixing element, the intention of the patent is to force material, *under compression*, through this mixing element.

The Dray mixer does not seem as popular as the Union Carbide and Egan mixers. Perhaps the reason is that, if the mixer is used as described, it appears that at least some material will bypass the mixing lands resulting in non-uniform shear.

IV) Double Wave: The double wave screw[14] developed by Kruder at HPM was tested with the die and downstream equipment.

[13] Ibid p 432.

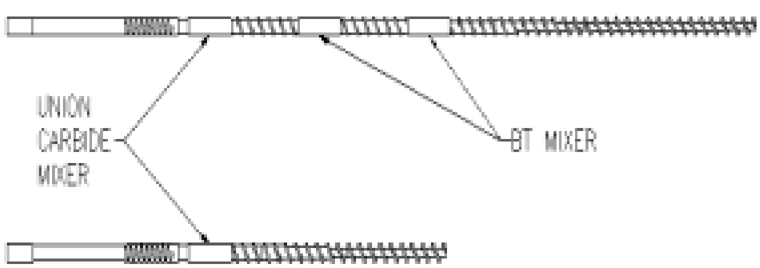
Double Wave Screw



The extruder was 1.25 inch diameter so it should receive a significantly better mixture (about 6 times better) in each flight than on the 5/8 inch screw it was tested against. We would expect a six fold improvement in distribution. Further, the constant shifting of material over the barrier, and the resulting shear, has been thought to have some dispersive mixing capability.[15]

V) The BT Mixer: The BT mixer is similar to a Union Carbide mixer and the Dray mixer. In terms of physical construction, a BT mixer is essentially a Union Carbide mixer where the inlet channel is open but not necessarily tapered as in a Dray mixer. It is further distinguished by:

1) **Location:** The Union Carbide and Dray mixers are usually located *after* the compression section of the screw or after the barrier flight in a melt separation screw. In other words, it is located after the melting zone. The BT mixer is an integral part of the melting zone of the screw. Therefore, the viscosity is much higher. This allows the creation of higher critical stress levels required for elongational dispersion. The drawing below shows the location that we used.

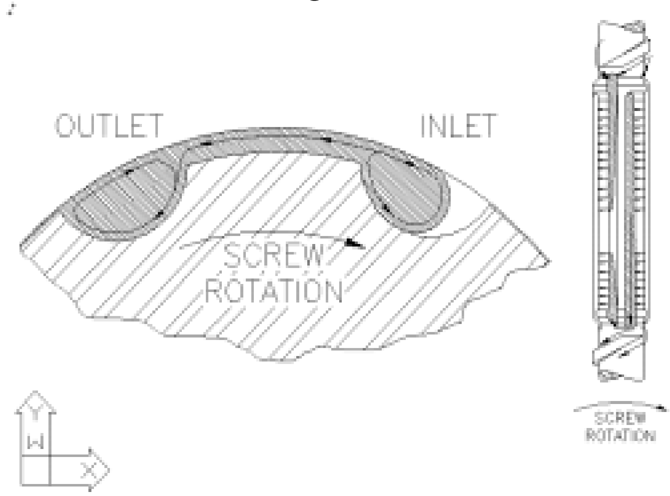


2) **Mode of Operation:** In order to operate properly, only the minimum pressure is used to deliver material to the inlet channel. Once material enters the inlet channel, what is normally thought of as the barrier (in the Union Carbide mixer) becomes the pump itself. When the pumping capacity of the barrier exceeds the inlet flow, the inlet channel will be partially emptied. The material that approaches the barrier will then be in elongation where dispersion can take

[14] Kruder, G., U. S. Patent 3,870,284.
[15] Rauwendaal, Mixing In Polymer Processing, Marcel Decker, 1991, p 178.

place. This may be achieved by starve feeding or screw design. Starve feeding adds a great deal of flexibility to the process and allows optimization of the process.

In twin screw extruders, lobal elements are commonly used to promote mixing. White shows the flow pattern in a bi-lobal kneeding disc.[16] Cooling experiments—the subject of another paper—have verified that the flow pattern is a combination of the circulating flow and the down channel flow.

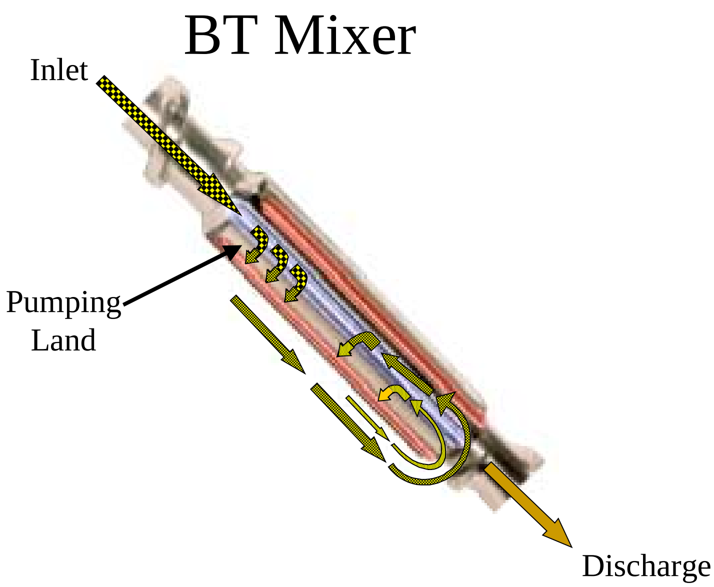


The BT Mixing Element

Both views show a starved inlet channel. The barrier flight, between inlet and outlet channels, becomes a pump and fills the outlet channel. In the right hand view, the inlet flow is ideally limited to an amount below the pumping land. The pumping land draws off the material in the inlet channel until the supply is exhausted. This means that a portion of the inlet channel can be empty.

Note, however, that since the inlet channel is open at the bottom, the pumping land creates pressure and material is then delivered to the region just before the flight. Some flow of material is intentionally directed backwards into the empty portion of the inlet channel. Since this material would already have been mixed, some material is exposed to remixing. This is shown schematically below:

[16] White, Twin Screw Extruders, Hanser Publishers, NY, 1990, p 229.



Many immediate ideas come to mind that might encourage or reduce the amount of remixing. For example additional feed rate to fill the end of the inlet channel would prevent remixing. Most importantly, there is an opportunity to direct the material through second or third pumping lands. Thus, the elongational stretching would be repeated *within the mixer* and before the controlling modulus drops.

VI) First Experimental Apparatus For TPO:

As a control, the experiment used a 24/1 Randcastle extruder with a single 4 L/D Carbide (Maddocks), 0.020 radial barrier clearance, mixer located at the screw discharge. It was capable of either flood or starve feeding. The extruder included a breaker plate but no screens that might obscure the mixing effects. The extruder pumped into a 6 inch flexible lip film die, a 35 mil die gap, and a chill roll take-off.

The experimental apparatus consisted of the 50/1 L/D Randcastle extruder including a breaker plate without screens. It used the same starve feeder, film die, and chill roll. The 50:1 operated at the same temperatures and screw speeds during the experiment as the 24/1. A pressure gage was added between the first and second mixer to monitor pressures to insure that the channel before the second BT mixer was starved.

The 50:1 extruder screw design incorporated an identical Union Carbide mixer in the same location as the 24/1 extruder. The 50:1 L/D screw design was different only because it incorporated two 4 L/D BT mixers and 18 L/D's of conventional flighted screw channels. These differences, everything else being equal, would be responsible for any qualitative mixing changes observed in the film.

Finally, a double wave screw was used to process the same material.

VII) TPO Experiments:

A) Create A TPO: We wanted a challenge for a small single screw extruder that could show the difference between a typical 24/1 screw with a Union Carbide mixer and the experimental tool. The thermoplastic elastomer and the polyolefin chosen would likely be too challenging to produce a uniform mixture for a carbide mixer but might be practical in the experimental BT design. Unlike mixing simple fillers or colorants into polyethylene, this process involves making a useful polymer blend as a vinyl substitute. This involves some minimal threshold level of mixing stress rate rather than simple wetting or distribution. The development of the polymer blend can be seen visually as one material, the TPO, because the elastomer was colored gray.

The LDPD was Dow 640 and the elastomer was Teknor Apex 98-T0184G-95 Grey 2411.

B. **Procedures:**

1) Limited Mixing Tests: For flood and starved conditions, drop 1 or more pellets of the elastomer into the polyolefin and capture the mixed 10 mil samples.
2) Make Blends: For flood and starved conditions by weight, blend 0, 10, 20, 40, and 60% amounts of the elastomer into the olefin making films as thin as possible and at 5 mils, and 10 mils thick.

VII) TPO Process Conditions and Presentation:

A) General: A total of 97 samples were made. Key representative samples were either scanned or photographed depending on which technique produced better results. Basically, lighter samples were scanned until the limit of the scanner was reached with the darker samples. These were placed on a light box and photographed. Some of these were digitally enhanced but we limited this to the “auto equalize” function in PHOTO-PAINT 9 so as not to distort the pictures.

The two techniques produced results that more closely resemble what we can see by eye. However, tiny adjustments in the camera angle produced major changes in the appearance when photographed. For example, *Sample 71* looks slightly lighter than 55 or 58 when it is more heavily loaded. The actual sample is darker as you would expect.

Finally, while we made thinner samples to insure that the samples could be drawn at least to the 2 mil control of the 24/1, all the samples shown are 10 mil thick. All samples are within 10% tolerance (except for the edges which are always thicker on untrimmed cast films).

B) Temperatures: The 24/1 was a 3 zone barrel set at 300, 375, 375F starting at the hopper. The die was set at 375F. The 50/1 was a 4 zone barrel set at 300, 375, 375, 375F starting at the hopper. The die was set at 375F.

C) Output:

1) At 62 RPM: Flood feeding of the 24/1 at 62 RPM yielded 36 grams per minute. Starve feeding at 62 RPM of the 24/1 and 50/1 was set at 16 grams per minute (45% of flood feed screw).

2) At 100 RPM: Flood feeding of the 24/1 at 100 RPM yielded 56 grams per minute. Starve feeding was set at 28 grams per minute (50% starved) for the 24/1 and 50/1. Because of the 100 RPM starve fed results, we decreased the feed on the 24/1 in an attempt to improve mixing. This feed was set to 21 grams per minute.

VIII) Summary of TPO Results:

A) Flood Feeding, 24/1, 62 RPM, Limited Mixing:

Sample 1 shows the classic parabolic flow front (for a small extruder) of a single gray elastomeric pellet in the 10 mil film.

Sample 2 shows a darker flow front because two gray elastomeric pellets were introduced at once. This is typical of small extruders even though the pellets have passed through a Union Carbide Mixer.

Sample 3 (originally numbered 2A) shows two gray elastomeric flow fronts in a 10 mil film. This is because the elastomeric pellets were introduced 6 revolutions apart. This example shows what is to be expected from mixing in this machine. As elastomeric pellets enter this screw, each will form an individual flow front. Sometimes these flow fronts will overlap and sometimes not. This depends on the entry of the elastomer to the screw and results in non-uniform mixing.

Under very few circumstances could this be considered a good quality mix. Screens might ‘blur’ the effects of this poor mixing but the screw would still be a poor mixer.

B) Flood Feeding, 24/1, 62 RPM, Blends:

The polyolefin was processed without elastomer. A clear film with a minimum thickness of 2 mils was established at the temperatures chosen. We consistently were unable to make the material draw to a thinner gage of 1.7 mils as it tore at the die.

Samples 4, 6, 9, and 13 are 10, 20, 40 and 60% elastomer respectively. They show the same basic undispersed parabolic flow lines that the limited feeding experiments show. The greater the amount of elastomer, the darker the films. But the underlying poor mixing is still there as evidenced by the parabolic flow lines.

C) Starve Feeding, 24/1, 62 RPM, Limited Mixing:

Sample 15 shows two gray elastomeric pellets introduced at one time (as in *Sample 2)* but starve fed. The mixing is slightly better as the parabolic flow front is more diffuse. While one might be tempted to say that the quality of mix can then be measured by measuring the width of the flow lines, these flow lines are themselves evidence of poor mixing.

Sample 16 shows the effect of adding 15 elastomeric pellets. *Sample 17* shows the effect of adding 30 elastomeric pellets. We see a concentrated parabolic flow and nearly the same number of distinct flow lines as the number of pellets. As thirty pellets is two full L/D's of material, the screw is no longer completely starve fed. Nevertheless, the same experiment with the BT mixer will not show this result.

D) Starve Feeding, 24/1, 62 RPM, Blends:

Samples 19, 22, 26 and 32 are 10, 20, 40, and 60% elastomer respectively. These samples show the same slightly diffuse parabolic pattern with distinct flow lines very similar to *Samples 16 and 17*.

In general, the starve fed samples are darker when placed side by side with the flood fed samples because there is more overlap of the broader parabolic bands. Still, the dark parabolic bands are indicative of a lack of mixing as they represent concentrations of the elastomer.

E) Starve Feeding, 24/1, 100 RPM, Limited Mixing:

Sample 36 shows the effect of adding 30 elastomeric pellets at higher speeds. There is no significant change in the pattern compared to *Sample 17*.

F) Starve Feeding, 24/1, 100 RPM, Blends:

1) S*amples 19, 22, 26 and 32* are 10, 20, 40 and 60% respectively. They are inferior to the 62 RPM 24/1 blends. Possibly, this is due to unmelted material because of the shorter residence time. Additional evidence for this conclusion is that there are larger dark gray inclusions—apparently agglomerations of elastomer.
2) In an attempt to improve the mixing, we further reduced the feeding to only 38% of the flood fed output. *Sample 50* is representative of these additional

starved samples, 10% elastomer. It is slightly better mixed because the dark inclusions, noted immediately above, are lessened. The parabolic flow lines seem slightly more blurred. Otherwise, it is still a poor mix.

G) Starved Feeding, 50/1, 62 RPM, Limited Mixing:

1) Polyethylene was processed without elastomer. We consistently made 1 mil film. This is a significant improvement over the 24/1 results where we could not make films under 2 mils.
2) Two elastomeric pellets were introduced into the feed as in *Sample 15*. This was done 5 separate times. We never found the parabolic flow front from the two pellets. That is, there was no discernable flow front caused by the two pellets that could be distinguished from the background haze of the polyethylene.
3) Ten elastomeric pellets were introduced. When a white piece of paper was placed behind the film, a parabolic flow front could be distinguished as in *Sample 52*.
4) *Sample 53* shows the addition of 15 pellets of elastomer and should be compared to *Sample 16.* There is no distinguishable concentration of elastomer as evidenced by a dark parabolic lines.
5) *Sample 54* shows the addition of 30 pellets of elastomer. There are very slight flow front lines at the leading edge of the parabolic flow.

In all these cases, the samples are distinctly different from the previous 24/1 samples. The distinctive parabolic flow lines have vanished. Only *Sample 54* shows any pattern at all and this is extremely diffuse. It should be remembered that all 30 pellets were introduced at one time—as though it were temporarily flood fed for 2 L/D's.

H) Starved Feeding, 50/1, 62 RPM, Blends:

Sample 55, 58, 71, and 82 are 10, 20, 40, and 80% elastomer. There is no discernable pattern in the films even at 60%. The only discernable pattern in the film is in the machine direction as evidenced by die lines or bands of slightly different thickness from the nominal 10 mils.

I) Starved Feeding, 50/1, 100 RPM, Blends:

Sample 62, 74, and 85 are 20, 40, and 60% elastomer respectively. Unlike the higher speed 24/1 experiments, there is no discernable pattern in the films. However, there are occasional agglomerations, apparently elastomer, at these higher speeds at the 40 and 60% concentrations. Examples are circled.

J) Flood Feeding, 50/1, 62 RPM and 100 RPM, Limited Feeding:

Sample 96 and 97 show the effect of adding 15 and 30 elastomeric pellets with flood fed conditions. Compare this to *Samples 17, 36, 53, and 54.* In terms of a flood fed tool, these samples are much more uniform than the 24/1 samples. They can even be said to be vastly better than the starve fed 24/1 *Sample 17*. From that point of view, the samples show a vastly improved flood fed tool.

However, they are clearly inferior to the starve fed 50/1 samples. This is difficult to photograph and these prints are almost certainly worse. But, to the eye there is no doubt that the starved fed 50/1 samples are significantly better.

IX) Second Experimental Appartus For TPO:

A 24/1 1¼ inch extruder was set up at the same temperatures and output as the previous trials. The extruder was flood fed.

X) TPO Mixed By Double Wave:

A two pellet drop test was performed but it was difficult to find. A 10 pellet drop test—similar to sample 53. Sample 100 is the result. It is clearly superior to the UC mixer and starving could be expected to improve the results further. However, it is equally inferior to the flood fed sample 96 of the 50/1 BT mixer.

A 10 percent sample was made and processed as above.

XI) Third Experimental Apparatus For PP:

Set up a 24/1 extrusion cast film line same as previously described. Install the following screws:

A) No mixer, flood fed.
B) With a 4 L/D UC mixer, flood feed.
C) With the same screw, starve feed.
D) With a 4 L/D UC mixer and one BT mixer, starve fed.

Set up a 50/1 extrusion cast film line same as previously described with a UC mixer and two BT mixers, starve fed. Set up the cast film line as previously described.

XII) PP With Color Experiments:

On page 5 of this paper, the PP with color concentrate mixture is shown. To give some idea of the mixture, it is composed of four colors: yellow, white, red and blue. In the full grids, there are a total of 46 yellow color concentrate pellets, 8 red pellets, 3 blue and 3 white pellets. Note that grid 9 has two blue and one red pellet.

Process all materials at similar barrel profiles of barrel zones 325, 400, 430 (and the 4th barrel zone of the 50:1 at 430) and die at 430F. Process at 30 RPM for all experiments and hold the output at 16 grams per minute and 62 RPM for the starve fed experiments. (The 16 gram output was selected because of the difference in pumping rate of the extruder.) Extrude 50 feet and find the worst samples to display.

XIII) PP Results:

All films were scanned with the same parameters. Because the scanner passes light through the samples, the scanned extrudates look worse than in normal light to the eye.

Sample 102 is the color mixture processed through the 24/1 without a mixer. It shows every color pellet distinctly. Sample 103 is the carbide mixer flood fed. A general smoothing of the sharpest color lines is apparent. The output of the flood fed sample was 20 grams per minute. Sample 104 is the mixture processed through the 24/1 with a UC mixer and starve fed. Starve feeding seems to produce as big an effect, or even more, than the carbide mixer. Sample 105 is the same screw and one BT mixer and starve fed. Sample 106 is the mixture processed through the 50/1 with two BT mixers and one UC mixer as previously described. It is clearly the best and brightest.

Because we are showing the worst case examples, it may be hard for the reader to appreciate the total 50 foot sample. The general patterns in the film repeat at some time interval. For example, a bold pattern such as is shown in sample 102 repeats about every 18 to 24 inches. It is about the same for Sample 103. To find an example similar to 104 requires about 60 inches. To find an example like 105 requires about 120 inches.

XIV) Introduction To Flexible Vinyl Trials:

Small extruders generate so little heat in the screw that barrel cooling is usually not required. Watching the temperature controllers, it becomes obvious that the heat is coming from the heaters.

Flexible vinyl processes within relatively narrow conditions of temperature, shear, and time. If any of those parameters is too great or too little, the material does not properly extrude. When one parameter is lacking, say shear, then the other parameters can be adjusted, within limits, to compensate.

It has long been noted that small extruders do not extrude flexible PVC at the same temperatures as larger extruders. The assumption has been that this is because larger extruders have a naturally higher shear rate. As a consequence, when a small extruder such as a 5/8 inch unit processed flexible vinyl, time and temperatures were adjusted to find an optimal set of conditions.

In gaining experience with the BT mixer over the past year, it is apparent that the stretching of the polymer generates heat. We find enough heat is generated to require cooling over the mixers in some instances (such as when processing 40% wood flour and running at high speeds such as 300 RPM.

With these factors in mind, we wanted to know if flexible PVC would process at more conventional temperatures and to investigate color mixing.

XV) Fourth Experimental Apparatus For Flexible Vinyl PP:

Set up a 24/1 extrusion cast film line same as previously described. Set up:

A) With a 24/1 UC mixer
B) With a 50/1 UC mixer and two BT mixers as previously described.

Set up a 50/1 extrusion cast film line same as previously described with a UC mixer and two BT mixers, starve fed. Set up the cast film line as previously described.

XVI) Natural PVC:

Colorite 7011C2-02 was processed through the 24/1 extruder at barrel temperatures, starting at the first barrel zone, 280, 300, and 335F. The die was set at 335F. These temperatures were chosen because they are fairly typical of production temperatures. Initial screw speed was set at 107 RPM.

The material exiting the die was not completely fused or melted at these temperatures. Sample 107 shows a pattern characteristic of a vinyl that is too cold. The holes are caused by the inability to draw. Notice that the outside of the film is much smoother indicating a higher temperature. This is because the material takes a longer pathway to the outside of the die so that this material receives more heat.

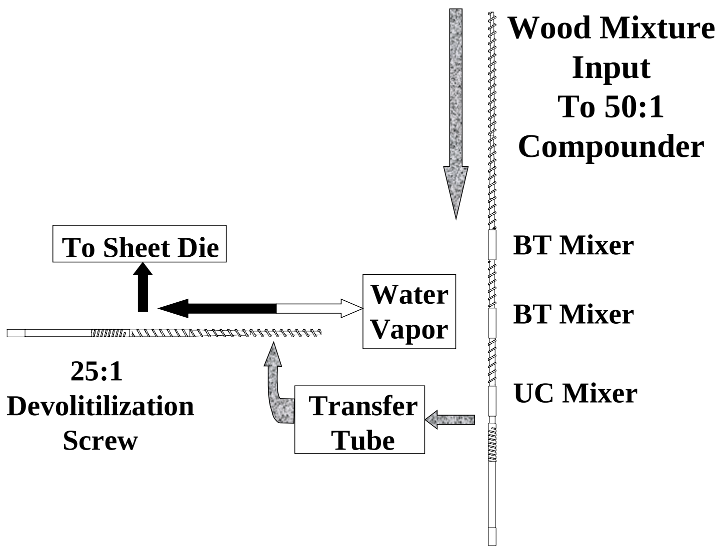
We raised the temperature of the barrel and die to 345F and the sample improved (Sample 108) but the vinyl was still too cold. After several stages, we raised the temperature to 355F. Slowly, we lowered the speed to until the best sample was produced at 30 RPM. This seemed the best that we could do, Sample 109. To the eye, though not easily scanned and printed, there are still chevron type imperfections.

The same material was process through the 50/1 with UC mixer and two BT mixers at barrel temperatures of 280, 300, 335, and 335 F barrel temperatures with the die at 335F. Sample 110, processed at 300 RPM and shows no chevrons to the eye and the only imperfects are die lines from lack of cleaning. (A similar sample was made at 107 RPM and is visually indistinguishable from the 300 RPM sample.) This shows extrusion at a much lower temperature and a much higher screw speed. It was noted that barrel zone 3 fan cooling was on during the trial nearly continuously. Apparently, the heat from elongation was sufficient to fuse the material.

XVII) Fifth Experimental Apparatus For Wood Flour:

A) Experimental Apparatus: This experiment used the same apparatus as discussed above as to the mixer. But, for the wood filled experiments, it was necessary to vent off the moisture from the wood in order to make sheet. We therefore added a Microtruder (5/8 inch diameter, single screw extruder, 25:1 L/D) in tandem with the 50:1 for total L/D of 75:1. The output was pumped through a 6 inch sheet die and into a 3 roll stack. This is shown conceptually below:

Flow Diagram of Wood Mixing System



There are several advantages of using tandem screws in the lab environment for venting. First, because you can adjust the relative screw speeds of the two screws, vent flooding is completely and easily eliminated. Second, the great length of the second screw—effectively the second stage of the screw—allows for maximal vapor removal by the surface renewal provided by a long rolling pool of the wood polymer matrix. Further, the length provides sufficient pumping length to overcome high die resistance and consequent high pressure. This is shown conceptually below:

For the final experiment, the viscosity of the wood filled, foamed, PVC was determined by a Viscom in-line rheometer. For this study, a premixed material was supplied and extruded in a conventional 24:1 extruder. The rheometer was placed at the end of the 24:1 screw.

B) Material: We wanted a mixing challenge for a small single screw extruder. Most often, particulate additives are limited to under a few percent because of screw jamming and aggomeration. So, we tested hard wood flour in 25 and 40% mixtures with 2 melt index LDPE pellets. This, we thought, would be an exceptional challenge as even twin screws have difficulty with this type of feed stock.

C) Procedures and Process Conditions: We starve feed the mixtures into the 50:1 hopper so that the pressure gage reading between the two BT mixers was zero ensuring a starve fed condition at a screw speed of 220 RPM. The speed of the 25:1 screw was then adjusted so that no vent flow occurred and this occurred at 105 RPM. The die and sheet were adjusted to make 0.030 inch sheet. The best temperatures found were barrel zone settings of 310, 330, 280, 280, for the 50:1 barrel and 280 for all other zones.

D) Results and Discussion: For both mixtures, a flexible sheet was produced such that the wood seemed relatively well mixed though there were some agglomerations. Both samples are smooth and flexible indicating that the wood is at least somewhat wetted. Given our previous experience with highly filled wood samples in single 24:1 extruders with UC mixers only, these samples are quite remarkable. Sample 98 is the 25% and Sample 99 is the 40%.

While both sheets were flexible and smooth, the 40 percent wood was much darker than the 25 percent mixture. Apparently, the wood has charred somewhat and this begs the question as to why and where the wood charred. There are several possibilities but the answer is not clear to us.

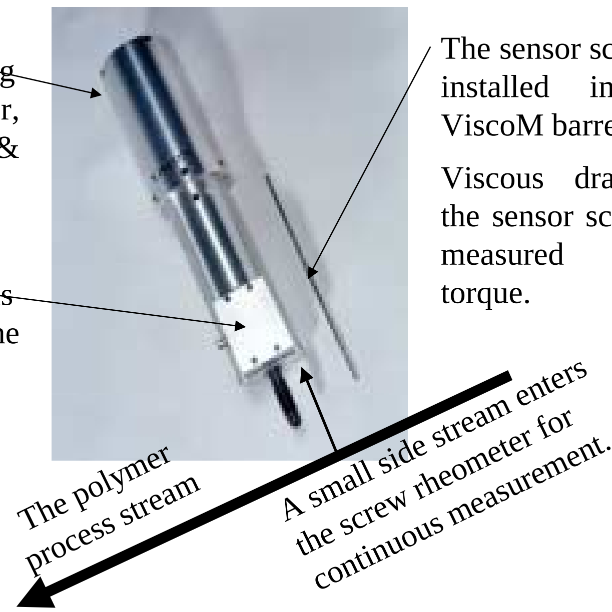
One possibility for which there is evidence is that the 50:1 zone 3 barrel temperature setting was raised significantly beyond set point by the heat of the mixture. Although excessive frictional heat is a very common problem in production sized extruders, it is quite rare in small extruders because of the low shear rates generated by small screws. This is why small extruders are often built without barrel cooling.

Nevertheless, the 50:1 was built with air cooling and yet the temperatures exceeded the setpoint by 32F during the 40% trials. Both the fan and temperature controls were checked. The fan was ‘On’ continuously during the trial and temperatures returned to normal immediately when the mixture was purged with LDPE. One of the possibilities is that the mixer put too much energy into the wood at the higher concentration.

XVIII) Measure foamed PVC Wood Filled Viscosity:

A) Experimental Apparatus: A Viscom In Line rheometer was used with a conventional 24:1 Microtruder. The flow stream was taken from the metering section of the screw at the discharge. The rheometer was equipped with a 0.020 inch die and a 0.010 inch channel depth screw. The apparatus can be seen below:

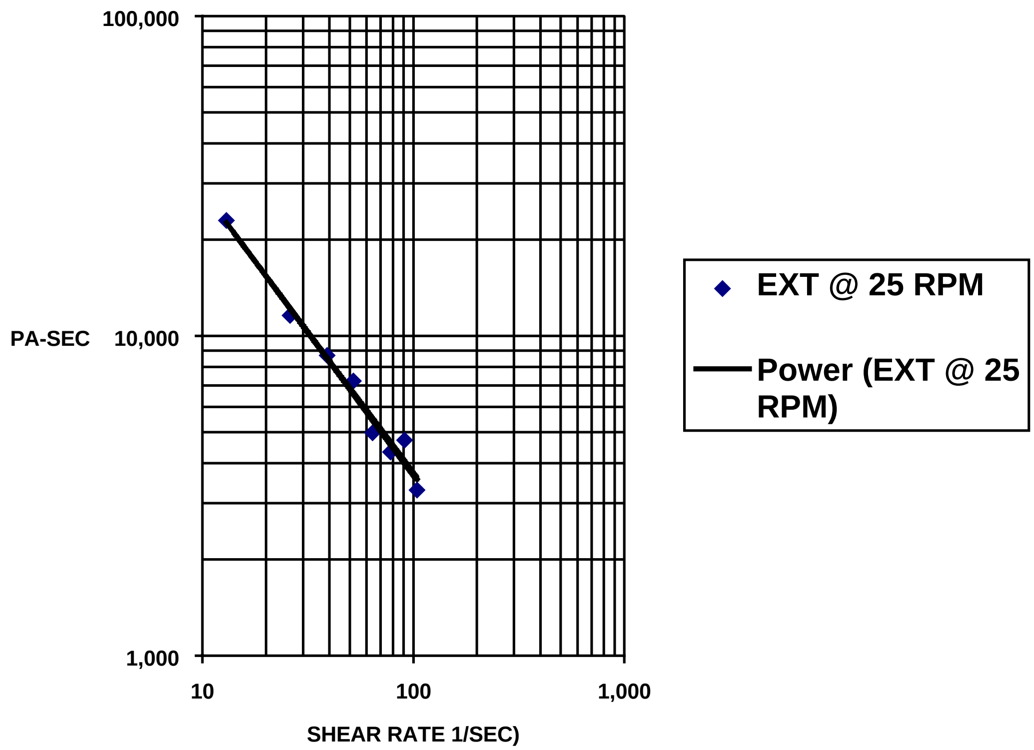
VISCOM RHEOMETER



B): Material: A pre-compounded rigid PVC with a foaming agent was supplied to us with wood fibers. The exact composition is proprietary.

C) Processing Conditions: The material was processed at a constant barrel temperature of 340F and screw speed of 25 RPM. The shear rate was varied as seen in the graph below.

VISCOSITY VS SHEAR RATE
RIGID PVC/WOODCHIP/FOAM MATERIAL
@ 25 RPM EXTRUDER RPM



B) Discussion of Results: The most surprising thing about the results is that there are results at all. We did not expect the limited channel depth of the rheometer was (only 0.010 inches) to pump the wood fibers since they were approximately ¼ inch and the channel width is only about 3/16 inch wide. Instead, we expected the wood chips to seize within the screw. This did not happen.

Further, in order to keep the foam within the structure, we used only a 0.020 die. We did not expect the material to exit the die and instead expected the material to seize within the tiny hole. This did not happen either.

Foams present their own set of difficulties when measuring viscosity as do wood filled materials and PVC. The versatility of the rheometer for this application is surprising.

IXX) Summary, Conclusions, and Speculations: Lab challenges for small extruders are sometimes surprisingly greater than in production and thus require equipment specifically designed for the lab rather than merely scaling down production extruders.

The traditional 24/1 lab extruder with a Union Carbide 0.020 barrier clearance was surprisingly ineffective, considering its reputation. The double wave screw was better though it did not disperse the elastomer.

Starve feeding does improve mixing in all cases in this study. By itself, this is inadequate to the task of mixing the compound with the 24/1 screw studied. Starve feeding was most effective when used with the BT mixer probably because it helped optimize the elongational mixing.

Regarding the success of this mixer test, we can at least say that the BT mixer is extremely useful in these applications. It appears to be a different “species” of tool because the mixing is fundamentally different. Apparently, some critical stress exists that is not present in a standard UC or Double Wave mixer. Additional testing will further define its range.

Although the 100 RPM samples showed signs of undispersed elastomer, no attempt was made to decrease the feeding which may have aided in dispersion of the agglomerates.

It is very interesting that for two materials (LDPE and flexible vinyl) the 50/1 was capable of making much thinner films at the same temperatures as the 24/1. The ability to make thinner at low temperatures often defines a good processing tool.

The exact reason why the BT mixer allowed the creation of thinner films is unclear. It may be that the additive package from the vendor was better mixed and allowed the material to be further drawn. It may be that heat was generated at the molecular level such that a better melted extrudate existed.

In any event, we have long observed that small extruders seem to require higher temperature settings to obtain the same thin film thickness that larger extruders achieve. These results imply that the 50/1 may scale better than merely keeping the L/D the same as a larger extruder.

In cooling experiments that will the subject of another paper, the BT mixing section is seen to elongate flow as described.

The BT mixer, and mixers that are now being built to double and triple pass the material within a single mixer, are significant advancements in the lab and low output arena. It is our intention to scale up to larger, production oriented, horizontal single screw extruders. Because single screws are much better at generating higher and more stable pressures than twin screw extruders, this may represent the potential to do in-line compounding with its consequent advantages.

These tests suggest that the BT increases mixing that have heretofore been consigned to twin screw applications. The keys to successful design would appear to be at least:

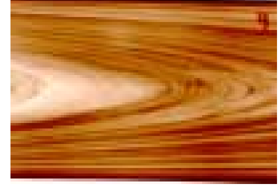
1) Low compression before the mixer, i.e. 1.2 to 1.8, the preferred amount depending on material and whether starve feeding is to be used.
2) Changing mixer length and radial pumping clearance as the controlling modulus drops.
3) Opening the inlet channel to prevent accidental jamming, insure non-compaction of components, and allow the chance of remix.
4) At the lab scale, L/D's of sufficient length (about 50/1) to provide adequate energy in the material to prevent jamming.
5) At the production scale, double and triple passing within the mixer to provide multiple elongational pathways before the controlling modulus drops greatly.

There remains much work to be done including a mathematical analysis. However, this patent pending design shows great promise for production and has now become a serious consideration for lab applications. Future studies are planned.

The rheometer work demonstrates unique versatility at low cost in a simple, reliable apparatus.


Sample 1

Sample 2

Sample 3

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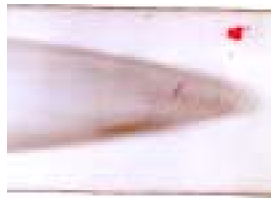
Sample 6

Sample 9

Sample 13

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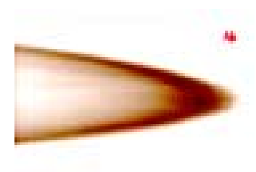
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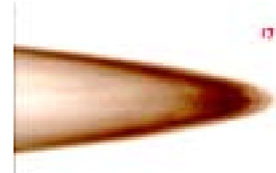
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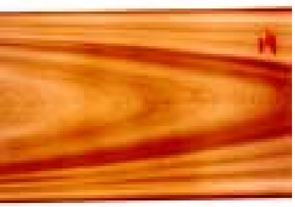
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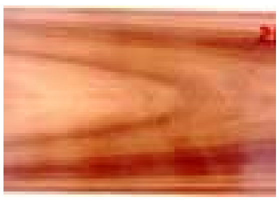
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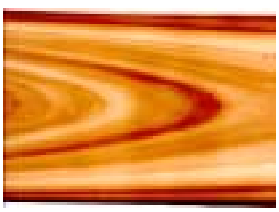
Sample 26

Sample 32

Sample 36

Sample 42

Sample 50

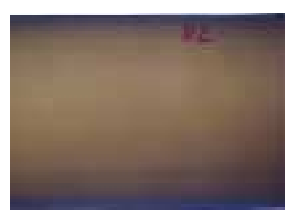
Sample 52

Sample 53

Sample 54

Sample 55

Sample 58

Sample 71

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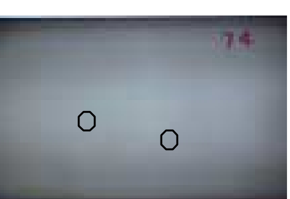
Sample 62

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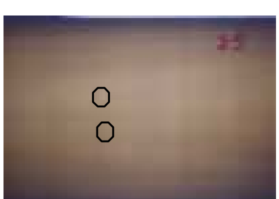
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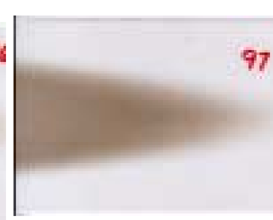
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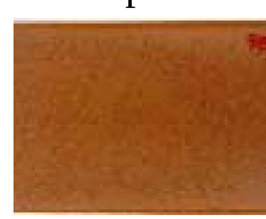
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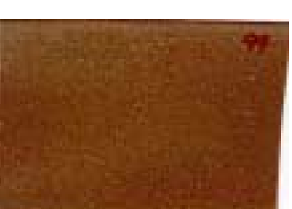
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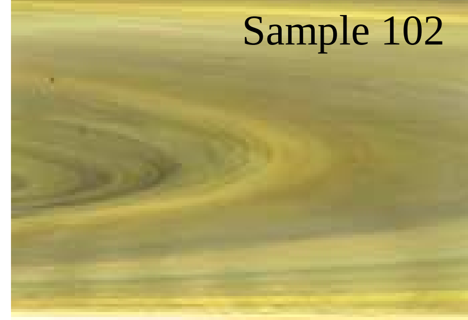
Sample 100

Sample 101



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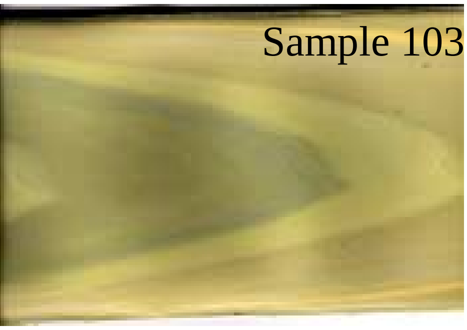

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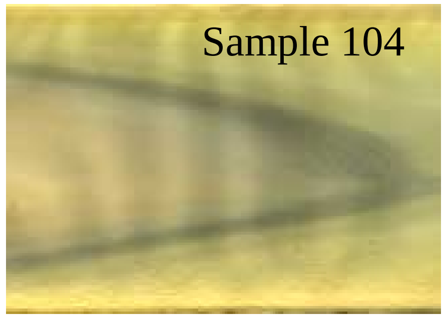

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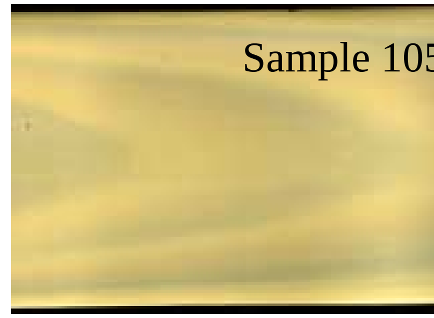

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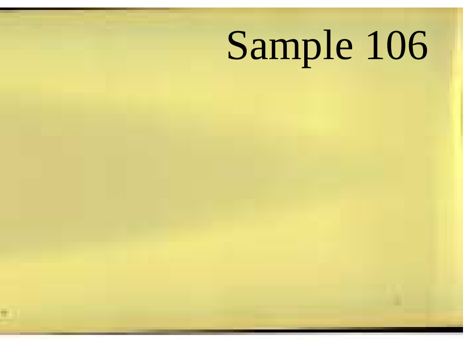
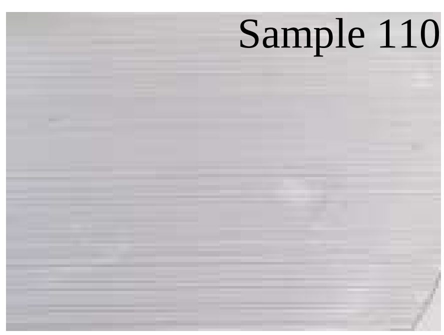


Sample 106

Sample 107

Sample 108

Sample 109



Sample 110