Hydrocarbon resins (HCR) can be extruded with polypropylene resin (PP) directly from a dry blend to save tolling costs in a masterbatching process. A glassy, low-molecular-weight polymer, HCR is compatible with a wide range of polymers. When used in film, it significantly improves barrier properties, clarity, stiffness, and many other attributes. Because of its low softening temperature and low viscosity, most applications use HCR masterbatch to avoid extrusion instability and poor mixing. In most applications, up to 15% to 20% of HCR are used in order to optimize the final properties. If an extrusion system can be developed to directly feed the HCR to the extruder, a significant cost saving can be achieved.

**Polymers Properties**

**HCR**

HCR is used mostly as a modifier in adhesives to improve tack, lower viscosity, and provide other properties. It is a glass-like, brittle, and sticky polymer produced by polymerization of byproduct streams resulting mostly from the cracking of petroleum hydrocarbons for ethylene production. The three principal raw-material streams to produce HCR are linear C5s such as piperylene and amylene, cyclic C5s such as cyclopentadiene, and aromatic C9 and C10 fractions, heavy in reactive monomers such as styrene. All hydrocarbon resins can be hydrogenated to improve color, odor, and stability, as well as modifying compatibility.

**PP modified with HCR**

The most popular application of PP-HCR blends is in polypropylene homopolymer film, especially biaxially oriented film. Figure 1 illustrates the advantages of adding HCR in biaxially oriented PP film. Many other applications also take advantage of HCR’s unique characteristics.

**Experimental**

**Material handling**

Handling of HCR needs special caution. The brittle pellets tend to generate fines, which can be dusty and sticky. A well-designed conveying system that can handle the fines is strongly recommended.

For this study, a multicomponent loss-in-weight feeding system was used to prepare the HCR and PP blend in line. The feed streams entered an in-line blender before dropping into the extruder hopper. The ratio of PP to HCR was adjusted by the individual feeding rate. The proportion of HCR in the feed stream ranged from 0% to 20% during the trial.

**Extruder**

A 2.5-inch, 30:1 L/D well-instrumented extruder was used for the
trial. The extruder had a 75-HP DC drive with maximum screw speed of 140 rpm. Five pressure transducers were located along the extruder, as shown in Figure 2, to measure the internal pressure developed by the screw. An immersion melt thermocouple was used to measure the true melt temperature.

To simulate the back pressure from a die, a restrictor valve was used to adjust the head pressure normally encountered in a commercial process. Samples of extrudate were taken at the valve discharge to analyze the dispersion of the HCR in the PP phase.

Screw A was designed for polypropylene resin. The screw geometries shown in Figure 3 are:
- F: Feed section length, 9 D
- Hf: Feed section depth 0.540 inch, square pitch
- T/B: Transition/barrier section, 12 D
- Pm: Major flight pitch 3.50 inches
- Pb: Barrier flight pitch 3.75 inches
- Melt channel depth: 0.115 inch–0.318 inch
- Solid channel depth: 0.550 inch–0.130 inch
- Barrier flight undercut: 0.065 inch
- Metering section length: 10 D
- Metering section depth: 0.310 inch
- Mixing section length: 6 inches

Screw B was designed to maximize the output rate of polyolefin resin in general. The screw geometries shown in Figure 3 are:
- F: Feed section length, 6 D
- Hf: Feed section depth 0.480 inch, square pitch
- T/B: Transition/barrier section, 16 D
- Pm: Major flight pitch 3.50 inches
- Pb: Barrier flight pitch 3.75 inches
- Melt channel depth: 0.250 inch (constant)
- Solid channel depth: 0.480 inch–0.135 inch
- Barrier flight undercut: 0.045 inch
- Metering section length: 9 D
- Metering section depth: 0.250 inch
- Mixing section length: 7 inches

Screw C was designed specifically for blown-film-grade low-density polyethylene. The screw geometries shown in Figure 3 are:
- F: Feed section length, 5 D
- Hf: Feed section depth 0.495 inch, square pitch
- T/B: Transition/barrier section, 17 D
- Pm: Major flight pitch 3.50 inches
- Pb: Barrier flight pitch 3.75 inches
- Melt channel depth: 0.220 inch–0.415 inch
- Solid channel depth: 0.480 inch–0.135 inch
- Barrier flight undercut: 0.080 inch–0.050 inch
- Metering section length: 9 D
- Metering section depth: 0.415 inch
- Mixing section length: 7 inches

Resins
PP4712E1 polypropylene from ExxonMobil Chemical Co. was used as the PP component. This grade is a homopolymer used mainly for film applications, such as BOPP film. It has a nominal MFR of 2.8 g/10 min and typical density of 0.90 g/cm³. The peak melting point is 162°C.

The Oppera PR100A HCR, from ExxonMobil Chemical Co., used in this experiment has a ring and ball softening point of 135°C–140°C and Tg of 85°C. Its typical molecular weight of 675–986 is very low compared to PP. Since it is glassy and brittle, the pellet size is somewhat nonuniform and some fines occur.

Procedures
The percentage of HCR in the PP blend ranged from 0%–20% in 5% increments. For each blend ratio, extrusion performance at 40 rpm and up to 120 rpm was evaluated. The output rate, pressure profile along the barrel, and melt temperature were recorded for each screw speed after the extrusion condition reached a steady state.

Results and Discussion
Overall observation
To avoid premature softening and melting of HCR at the throat of the extruder, it was necessary to have extruder

![Fig. 2. Extruder setup.](image)

![Fig. 3. Screw designs, A, B, & C.](image)

![Fig. 3. Screw designs, A, B, & C.](image)
throat cooling. Without it, the fines of the HCR tend to soften and stick to the hopper base and hinder smooth feeding of the blend.

The irregular shape of the HCR pellets did not seem to affect the homogeneity of the blend or the free flowing of the blend in the extruder hopper. The transition from PP to PP/HCR blend during extrusion was smooth, and it reached a steady state in 20 to 30 minutes.

**Performance of screw C**

The screw design has a strong influence on the extrusion performance of the blend. Screw C, designed specifically for LDPE, has a shorter feed section and low compression ratio. It was not possible to achieve a steady extrusion state with the PP/HCR blend. Surging occurred under most extrusion conditions. It is believed that the short feed section and low compression ratio created a solid plug at the beginning of the barrier section, where significant volume compression occurred.

Because the blend has a higher melting point and heat of crystallization than polyethylene, the screw design does not allow sufficient residence time to convey the polymers before melting occurs and the compression of the solid bed can be applied. Further, the highly crystalline polypropylene homopolymer is not as compressible as LDPE. Hence, the solid-bed plugging at the early stage of the screw causes the melting to become unstable. Because of the deep metering depth, the low melting rate at the barrier section was not able to match the conveying rate of the metering section, further causing the screw to surge.

**Performance of screw B**

This screw has a longer feed section, square pitch, and shallower metering section than screw C. It was possible to obtain a steady extrusion condition for all blend ratios.

*Figure 4* compares the output rate for different percentages of HCR in the blend. It is interesting to note that the specific output rate is very high up to 40 rpm. Then the output rate tapers off and remains almost the same up to 120 rpm at all blend ratios. In fact, there is a slight decrease in output around 80 rpm.

In this screw design, the flight pitch increases from 2.5 inches at the feed section to 3.5 inches at the barrier section, and the channel depth changes from 0.480 to 0.135 inch over 16.5 D. Therefore, the solid-bed compression is very gradual and the polymer has a longer residence time to preheat and initiate melting, resulting in high output rate at low screw speed.

*Figure 5* compares the internal pressure profiles along the extruder at 40 and 80 rpm for PP and 20% HCR blend. Note that at 80 rpm, the screw is basically starved until the last 20% of the screw length. There must have been a blockage at the early stage of the screw, where it was not capable of developing sufficient pressure at that screw speed.

**Performance of screw A**

This screw was designed for polypropylene. It has a long feed section (9 D) and constant melt and solid channel widths. Its longer and deeper feed section provides a longer residence time for the polymer blend to reach a higher temperature with the solid-bed compression at the onset of the barrier flight.

The output rates for different blend ratios are shown in *Figure 6*. As is typical in screw performance, the output rate increases monotonically with increasing screw speed.
The difference in output rate between the different blend ratios is also much smaller than with screw B.

**Effects of barrel temperature**

*Figure 7* shows the output rate for 15% HCR at 80 rpm using screw A. It shows that the barrel temperature affects the output significantly. Since PP is a major component of the blend, a higher barrel temperature setting, especially at the melting section, significantly improves the output rate of the blend. This indicates the melting rate could be the rate-limiting factor.

Because of the low softening point of the HCR, it is not clear how the higher feed-section temperatures affect solid-bed conveying. It is possible that a low feed-section temperature setting improves solid conveying by delaying the melting of the HCR, which may act as a lubricant and hinder solid conveying. However, because of the very low viscosity of HCR, the high feed-section temperature may not cause significant slippage in the solid conveying zone. The last condition on the right-hand side of *Figure 7* seems to confirm this argument.

**Internal pressure profile**

*Figure 8* shows pressure profiles along the extruder under different temperature profiles. Note that for all conditions except condition F (the highest temperature on all zones), the early part of the screw exhibits no or very low pressure, especially in conditions A, B, and E.

The low pressure indicates that the shear stress between the solid bed and the barrel is low and therefore viscous shear heating would be less than when there is high internal pressure.

At the highest-output condition (F), high pressure is observed at the 6 L/D location and remains at a higher level compared to the lower-output conditions. Based on this observation, it is possible to modify the barrier flight design to relieve this high pressure early, and raise the pressures downstream, which would increase the output rate.

**Specific energy**

Once melted, HCR has a very low melt viscosity because of the low molecular weight of the polymer. Therefore, the addition of HCR significantly decreases the overall melt viscosity of the blend, resulting in lower extruder torque, horsepower consumption, and melt temperature.

The specific energy, expressed in hp-hr/lb, can be used to measure the energy consumption. The lower the specific energy, the lower the viscous shear heat dissipation, and therefore a lower melt temperature can be expected. *Figure 9* compares the specific energy for all blends under the same temperature profile for screw A.

**Dispersion of HCR in PP phase**

In order to produce a consistent product with attributes incorporating HCR, it is necessary that HCR be uniformly dispersed in the PP phase. With a barrier flight and a Maddock-type mixing section to enhance shear mixing, good dispersion of the HCR in PP is expected.

To verify if the polymer blends were well dispersed, samples with various blend ratios and output rates using extrudate from screw A were analyzed by extraction and scanning electron microscopy (SEM).

In an extraction test using toluene, no HCR was detected in the extracted solvent, indicating that HCR is well-dispersed in the PP matrix. At low SEM image magnification, we did not observe vacuoles or the presence of a sec-
ond phase formed by the undispersed HCR. At high magnification, it appears that HCR is well-dispersed in the amorphous regions such as the boundary of the spherulites and between the lamellae inside the spherulites. Figure 10 compares the images at 100X and 1000X for the 20% HCR blend extrudate at 100 rpm.

Conclusions

The output rate of PP and PP/HCR blends under the same condition is shown in Figure 11. Also shown are two optimized process conditions for the blend. It clearly indicates that PP/HCR blends can be extruded at a rate near the neat PP output rate. Similar to polypropylene extrusion, a high barrel temperature profile is desirable to achieve a higher output rate.

With a non-pneumatic raw-material–handling system and a well-designed screw, neat HCR could be dry blended and extruded directly with PP in a single-screw extruder to enhance the properties of PP. This approach eliminates the need to use a higher-cost HCR masterbatch. A steady extrusion with well-dispersed extrudate can be achieved to produce the desired product.

References

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Note: The authors presented a version of this paper at ANTEC® 2011 in May in Boston, Massachusetts, USA.
Plenary Speaker:
Kai Syrjälä, Ph.D., Nokia
Plastics Injection Molding & Tool Making: Challenges in China and Future Visions

Many plastics companies now have suppliers in China owing to cost-performance advantages and high-volume capabilities, noted Dr. Syrjälä. In addition, because of China’s large clusters of electronics companies and moldmakers, the country has been ramping up its automotive industry. Dr. Syrjälä’s presentation will illustrate current working models and practices in tool and mold manufacturing in China, focusing on how to succeed, maintain progress, and manage quality. He will also discuss what can be expected in the future.

Dr. Syrjälä is Director, Tooling and Molding Sourcing, at Nokia, and has led R&D teams all over the world. He is also responsible for the development and maintenance of Nokia’s global 3D-CAD systems and works with industrial designers on the company’s key products. Nokia was one of the first companies to use full solid modeling to take plastics from “style to steel” with short lead times. Dr. Syrjälä has been active in implementing new business models between Nokia and its suppliers in China.