Technical Paper

Productivity Advantages of Lightweight Injection Molded Thermoplastics Enabled by 3M™ Glass Bubbles

Andrea C. Charif, Steve E. Amos, Erik LaBelle, Kelly Denman, 3M Company
Shannon Bollin, Megan Shewey, Patricia Tibbenham, Ford Motor Company

ABSTRACT

Hollow glass microspheres from 3M can offer multiple advantages in injection molded plastics, including lightweighting, processing improvements, and dimensional stability. In this study, formulations with hollow glass microspheres were created to meet the specifications of existing materials and determine the effect on cycle time, processing conditions and mechanical properties using a research tool developed by Ford Research containing pressure and temperature transducers. Both polypropylene and polyamide formulations were evaluated from multiple material suppliers. Ford in conjunction with 3M found savings and improvements in both cycle time and processing conditions with mechanical properties meeting existing specifications.

INTRODUCTION

3M™ Glass Bubbles are low density, free-flowing powders consisting of thin-walled unicellular glass spheres. When used with other reinforcing fillers, in an optimized formulation, they can provide excellent weight reduction, performance, processing and dimensional stability characteristics. Glass Bubbles can also reduce mold cycle times by causing the thermoplastic parts to cool faster in the mold.[1]

The cooling time of molten plastic in the injection molding process can be estimated by calculating thermal diffusivity (α). This material property is the measure of a material's ability to transmit heat relative to its ability to store heat (Equation 1).

Equation 1. Thermal diffusivity

$$\alpha = \frac{k}{\rho C_p}$$

α = Thermal diffusivity $\qquad \rho$ = Density
k = Thermal conductivity $\qquad C_p$ = Specific heat capacity

All process parameters kept constant, materials with higher thermal diffusivity require shorter cooling times (Equation 2). Glass bubbles increase the thermal diffusivity by decreasing the density and composite heat capacity, thus increasing cooling rates.

Equation 2. Theoretical Cooling Time for an Injection Molded Plate

$$t_c = \frac{h^2}{\pi^2 \alpha} \ln\left(\frac{4}{\pi} \frac{T_{melt} - T_{mold}}{T_{eject} - T_{mold}}\right)$$

t_c = Cooling time $\qquad \alpha$ = Thermal diffusivity
h = Part thickness $\qquad T$ = Temperature

Initial work at 3M on PP tensile bars showed decreased part temperature with increased glass bubble content. Reducing cooling times by as much as 37% in unfilled PP at 20wt% GB loading. In glass fiber filled formulations, cooling time reduction was as high as 25%. The smallest cooling time reductions were seen in formulations containing talc.[2] Additional work by 3M and SKZ Institute showed variability in cycle time reduction depending on base resin and additional fillers as well. The focus of this paper is to present a cycle time study using commercially available thermoplastic compounds on a larger part with advanced process characterization instrumentation to help further understand the effect of glass bubbles on cycle time and processing improvements.

EXPERIMENTAL

Materials

The glass bubbles used for this study were 3M™ Glass Bubbles iM16K, which have a density of 0.46 g/cc and an isostatic crush strength of 16,000 psi.
All of polypropylene and polyamide 6,6 materials were compounded by commercial suppliers.

Formulations

The formulations evaluated in the study are summarized in Table 1.

Table 1. Experimental Formulations

Polymer	Incumbent Filler		Replacement Filler		
PP	20% T		5% GF	5% GB	
PP	20% GF	10% M	20% GF	10% GB	
PA66	8% GF	10% M	7% GF	10% GB	3% M

T: Talc; GF: Glass Fiber; GB: Glass Bubbles; M: Mineral

Tool

The tool used in this study, shown in Figure 1, was a Ford Research Beam Tool that contains a 14” beam, a tensile bar, a flex bar, 2 pressure transducers and 5 thermocouples.

Figure 1. Ford Research Beam Tool

Processing conditions

Processing conditions for both the incumbent and GB materials for each formulation are summarized in tables 3, 6 and 9.
Nozzle and tool temperatures recommended by material supplier are referred to as Standard conditions. Lower nozzle and tool temperatures, to simulate a condition that might be run at a supplier to maximize output, are referred as Optimized conditions.
After process stabilization a minimum of 10 parts were sequentially collected and evaluated for each formulation and under each set of process conditions.

Temperature Monitoring

Temperature images of the molded samples were taken using a Thermal FlirONE camera and analyzed by FLIR Tools. Images were always taken at precisely 18 seconds after ejection; this interval included mold opening time, part ejection and placement of the ejected part in front of the camera in a marked location, as shown in Figure 2. This ensured that all parts experienced the same cooling history before their thermal images were taken.

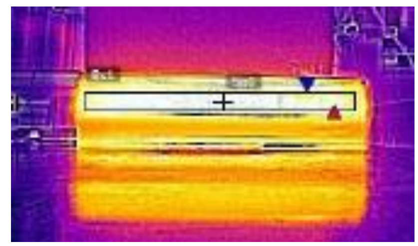

Figure 2. Thermal Image of Ford Research Beam Tool as it cools 18 seconds after ejection

Mechanical Properties

Mechanical properties of the injection-molded composites were measured using ISO standard test methods. A Micromeritics AccuPyc™ 1330 Helium Gas Pycnometer was used to measure density for all samples. An MTS frame with a 5000 lbf load cell and tensile and 3-point bending grips were used for tensile and flexural properties, respectively. A Tinius Olsen model IT503 impact tester and its specimen notcher were used to measure Notched Charpy impact strength of the molded parts. A Phenom Pro Desktop SEM was used to collect images of cold fractures of the molded parts.

Dimensional Stability

Digital Image Correlation (DIC) was used for the dimensional stability analysis of the different formulations. Multiple cameras used the high contrast random speckle pattern of the coated samples (Figure 3, top) to create a 3D mesh of the object as seen in Figure 3, bottom. With subsequent analysis of the 3D objects a cross-section profile is plotted and compared between the different formulations.

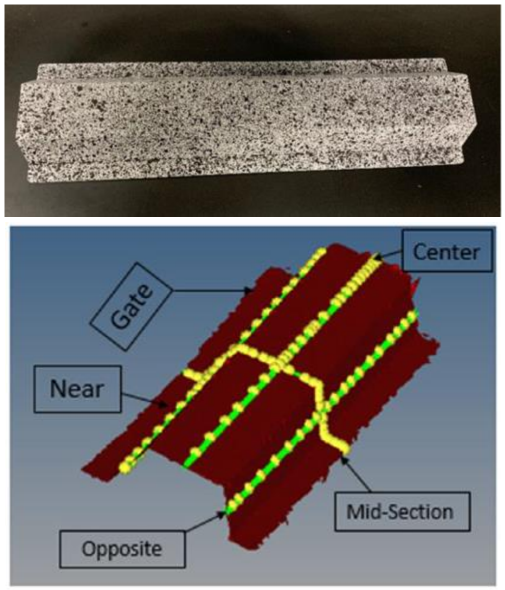

Figure 3. 3D mesh of beam tool for dimensional stability analysis (bottom) generated from coated samples (top)

RESULTS

Case Study I

20% Talc + Polypropylene (PP T20) to 5% Glass Fiber + 5% Glass Bubbles (PP GF5/GB5)

In the first case study a talc filled polypropylene (PP T20) was reformulated to a 5% glass fiber and 5% glass bubble filled polypropylene (PP GF5/GB5). SEM images in Figure 4 show uniform dispersion and high survival rates of glass bubbles.

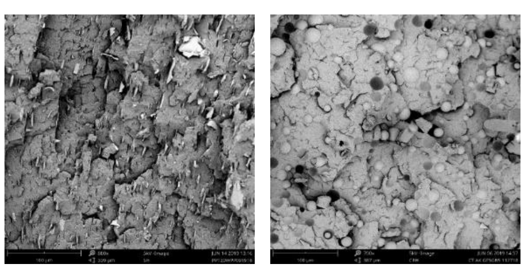

Figure 4. SEM Left - PP T20, Right - PP GF5/GB5

Table 2 shows the mechanical properties of PP T20 and PP GF5/GB5 processed under standard and optimized conditions. The part weight was reduced from 133 g to 115 g (-14%). The tensile strength increased 6% while tensile modulus decreased 20%. Notched Charpy impact shows negligible effect of changing material formulation at both room temperature and -40°C.

Table 2. Mechanical properties of PPT20 and PP GF5/GB5 under Standard and Optimized processing conditions

Component	PPT20 Standard		PPT20 Optimized		PP GF5/GB5 Standard		PP GF5/GB5 Optimized	
	wt %	vol%	wt %	vol%	wt %	vol%	wt %	vol%
Polypropylene	80	92	80	92	90	89	90	89
Glass Bubble iM16k	0	0	0	0	5	10	5	10
Talc	20	8	20	8	0	0	0	0
Glass Fiber	0	0	0	0	5	2	5	2
TS @ RT (MPa)	33.6		33.7		36.0		35.7	
TM @ RT (MPa)	3.3		3.4		2.6		2.8	
Strain at Break (%)	16.7		23.3		5.8		6.3	
NCI @ RT (kJ/m²)	2.9		2.5		3.0		2.5	
NCI @ -40°C (kJ/m²)	2.3		1.7		1.5		1.7	

Processing conditions for PP T20 and PP GF5/GB5 are summarized in Table 3.

Table 3. Processing conditions, cooling and holding time for PPT20 and PP GF5/GB5

Molding Condition	Barrel Temp (°F)	Mold Temp (°F)	Cooling Time (s)	Hold Time (s)
Standard	430	80	15	15
Optimized	390	80	15	10

Despite the decrease in post gate temperature measured in mold, the average part temperature did not show much difference between the two materials. Parts in the PP GF5/GB5 materials molded in the standard condition were 2°C cooler out of the mold than the baseline material. The cooling time was reduced by 2 seconds for the PP 5GF/5GB material for a 5% reduction in cycle time (Figure 5). Faster cycle times have been observed in the molding of larger parts.

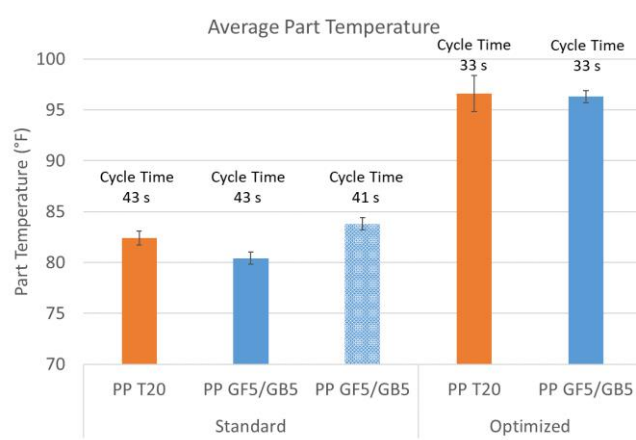

Figure 5. Average part temperature and cycle time PPT20 and PP GF5/GB5 under Standard and Optimized processing conditions

The maximum injection pressure dropped up to 18% depending on the molding conditions, this represents a potential opportunity to use a smaller press. The maximum post gate temperature dropped 5°F with glass bubble materials, which represents a possibility for faster cycle times.

Table 4. Maximum injection pressure and post gate temperature of PPT20 and PP GF5/GB5 under Standard and Optimized processing conditions

Material	Molding Condition	Max Injection Pressure (psi)		Max Post Gate Temperature (°F)	
PP T20	Standard	8345	↓11%	171	↓3%
PP GF5/GB5		7390		166	
PP T20	Optimized	9862	↓18%	168	↓4%
PP GF5/GB5		8099		162	

Cross-sections through the middle of the beam (Figure 6) show similar behaviors between the two materials. As expected, optimized conditions show more warp than the standard conditions.

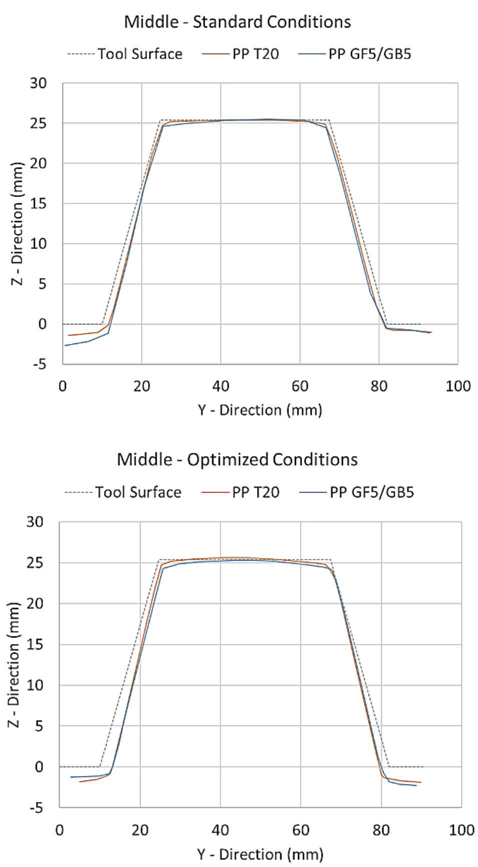

Figure 6. Cross-sections through the middle of the beam PPT20 and PP GF5/GB5 under Standard and Optimized processing conditions

Case Study II

20% Glass Fiber + 10% Mineral + Polypropylene (PP GF20/M10) to 20% Glass Fiber + 10% Glass Bubbles + Polypropylene (PP GF20/GB10)

In the second case study a 20% glass fiber and 10% mineral filled polypropylene (PP GF20/M10) was reformulated to a 20% glass fiber and 10% glass bubble filled polypropylene (PP GF20/GB10). SEM images in Figure 7 show uniform dispersion and high survival rates of glass bubbles.

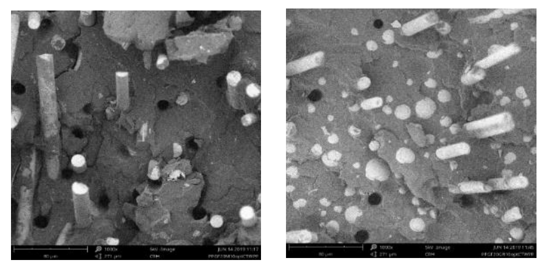

Figure 7. SEM Left - PP GF20/M10, Right - PP GF20/GB10

Table 5 shows the mechanical properties of both materials processed under standard and optimized conditions. The part weight was reduced from 143 g to 124 g (-13%). The tensile strength decreased 10% while tensile modulus decreased 8%. Notched Charpy impact shows a 20% decrease at room temperature and a 15% decrease at -40°C.

Table 5. Mechanical properties of PP GF20/M10 and PP GF20/GB10 under Standard and Optimized processing conditions

Component	PP GF20/M10 Standard		PP GF20/M10 Optimized		GF20/GB10 Standard		GF20/GB10 Optimized	
	wt %	vol%	wt %	vol%	wt %	vol%	wt %	vol%
Polypropylene	70	87	70	87	70	73	70	73
Glass Bubble iM16k	0	0	0	0	10	20	10	20
Glass Fiber	20	9	20	9	20	7	20	7
Mineral	10	4	10	4	0	0	0	0
TS @ RT (MPa)	69.9		65.4		64.8		58	
TM @ RT (MPa)	6.2		6.2		5.8		5.6	
Strain at Break (%)	3.1		3.1		2.1		2.1	
NCI @ RT (kJ/m²)	6.4		5.8		5		4.7	
NCI @ -40°C (kJ/m²)	4.9		4.4		4.1		3.9	

Processing conditions for PP GF20/M10 and PP GF20/GB10 are summarized in Table 6.

Table 6. Processing conditions, cooling and holding time for PP GF20/M10 and PP GF20/GB10

Molding Condition	Barrel Temp (°F)	Mold Temp (°F)	Cooling Time (s)	Hold Time (s)
Standard	430	140	15	15
Optimized	430	105	15	8

Significant cycle time savings were realized for both the standard and optimized processes. Parts in the PP GF20/GB10 material were 6°C cooler out of the mold than the baseline material. Standard molding conditions achieved a 4 second cycle time saving (8% reduction). Optimized molding conditions achieved a 5 second cycle time saving (11% reduction) (Figure 8).

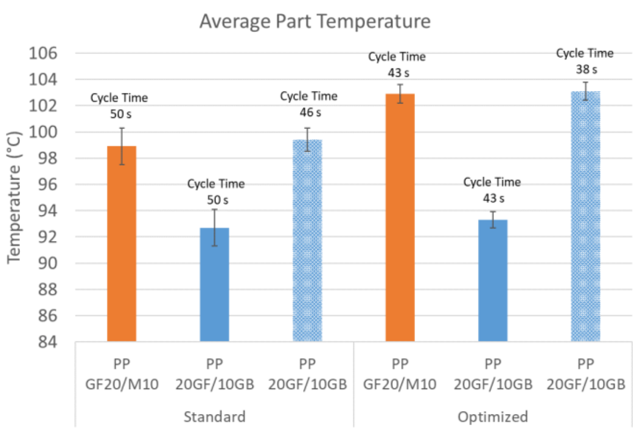

Figure 8. Average part temperature and cycle time for PP GF20/M10 and PP GF20/GB10 under Standard and Optimized processing conditions

The maximum injection pressure dropped 27%, a potential opportunity to use smaller press. The maximum post gate temperature dropped up to 14 °F with glass bubble materials, a possibility for faster cycle times. Hold pressure were also able to be reduced from 400 psi to 300 psi for glass bubbles materials (25% reduction).

Table 7. Maximum injection pressure and post gate temperature of PP GF20/M10 and PP GF20/GB10 under Standard and Optimized processing conditions

Material	Molding Condition	Max Injection Pressure (psi)		Max Post Gate Temperature (°F)	
PP GF20/M10	Standard	8783	↓27%	214	↓7%
PP GF20/GB510		6392		200	
PP GF20/M10	Optimized	8429	↓27%	187	↓2%
PP GF20/GB510		6170		184	

As in Case Study I the cross-sections through the middle of the beam show similar behaviors between the two materials. As expected, optimized conditions showed more warp than the standard conditions.

Case Study III

8% Glass Fiber + 10% Mineral + PA66 (PA66 GF8/M10) to 7% Glass Fiber + 3% Mineral + 10% Glass Bubbles + PA66 (PA66 GF7/M3/GB10)

In the last case study, an 8% glass fiber and 10% mineral filled polyamide 66 (PA66 GF8/M10) was reformulated to a 7% glass fiber, 3% mineral and 10% glass bubble filled PA66 (PA66 GF7/M3/GB10). SEM images Figure 9 show uniform dispersion and high survival rates of glass bubbles.

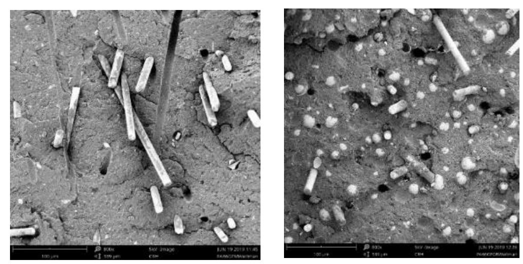

Figure 9. SEM Left - PA66 GF8/M10, Right - PA66 GF7/M3/GB10

Table 8 shows the mechanical properties of both materials processed under optimized conditions. The part weight was reduced from 160 g to 134 g (-16%). The tensile strength increased 17% while tensile modulus decreased 10%. Notched Charpy impact shows 25% decrease at RT and 10% decrease at -40°C.

Table 8. Mechanical properties of PA66 GF8/M10 and PA66 GF7/M3/GB10 under Standard processing conditions

Component	PA66 GF8/M10 Standard		PA66 GF7/M3/GB10 Optimized	
	wt %	vol%	wt %	vol%
Polypropylene	81	91	77	69
Glass Bubble iM16k	0	0	12	27
Glass Fiber	9	5	8	3
Mineral	10	4	3	1
TS @ RT (MPa)	61.7		72.2	
TM @ RT (MPa)	4.8		4.3	
Strain at Break (%)	2.5		3.3	
NCI @ RT (kJ/m^2)	4.4		3.3	
NCI @ -40°C (kJ/m^2)	2.6		2.3	

Processing conditions for of PA66 GF8/M10 and PA66 GF7/M3/GB10 are summarized in Table 9.

Table 9. Processing conditions, cooling and hold time for PA66 GF8/M10 and PA66 GF7/M3/GB10

Molding Condition	Barrel Temp (°F)	Mold Temp (°F)	Cooling Time (s)	Hold Time (s)
Standard	518	160	15	10

Parts in the P66 GF7/M3/GB10 material were 7°C cooler out of the mold than the baseline material. Standard molding conditions achieved a 3 second cycle time saving (6%). Further savings may possibly be realized with more process optimization (Figure 10).

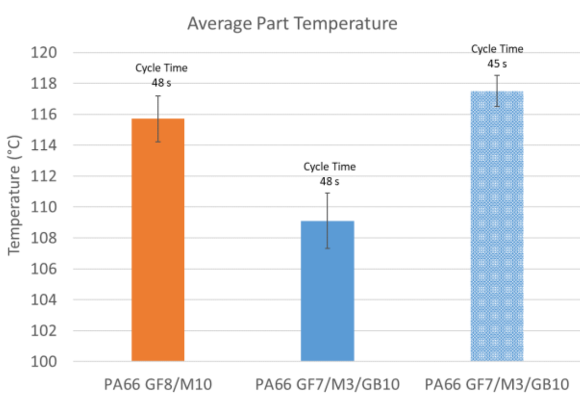

Figure 10. Average part temperature and cycle time for PA66 GF8/M10 and PA66 GF7/M3/GB10 under Standard processing conditions

In this case the maximum injection pressures increased significantly (74%), the GB material was rheology modified to have a higher viscosity than the baseline material at the request of end use customer. The maximum post gate temperatures drop up to 14°F (7%) with glass bubbles materials, a possibility for faster cycle times.

Table 10. Maximum injection pressure and post gate temperature of PA66 GF8/M10 and PA66 GF7/M3/GB10 under Standard processing conditions.

Material	Molding Condition	Max Injection Pressure (psi)		Max Post Gate Temperature (°F)	
PA66 GF8/M10	Standard	7386	↑74%	214	↓7%
PA66 GF7/M3/GB10		12847		200	

Cross sections through the middle of the beam show similar behavior between the two materials.

CONCLUSIONS

The addition of glass bubbles to material formulations resulted in cooler parts out of the mold and cycle time savings up to 11%. Different factors like glass bubble loading level, processing conditions and parts volume influence cycle time savings. Increasing glass bubble volume increased the cycle time savings. Savings could possibly increase with larger parts/more material volume. Materials developed are drop in (same shrink) for incumbent materials.

The presence of glass bubbles reduced the density of the injection molded parts while allowing the product properties to be retained to a large extent. Glass bubbles offered weight savings of ~15% depending on formulation. Also depending on the formulation Notched Charpy impact properties may be reduced. Future work includes formulation development for improved impact properties.

REFERENCES

1. Baris Yalcin et al. “3M™ Glass Bubbles iM16K for Reinforced Thermoplastics.” Technical Paper Issued by 3M Company.

2. Baris Yalcin et al. “Productivity Benefits of 3M Glass Bubbles in Injection Molded Thermoplastics via Increased Cooling Rates”. Technical Paper Issued by 3M Company.

3M Advanced Materials Division
3M Center
St. Paul, MN 55144 USA
Phone 1-800-367-8905

www.3M.com/autoglassbubbles

Issued: 08/2019