

Inter-Relationship Between Processing Conditions and Mechanical Properties of Blown Film from Different Polypropylenes and High Melt Strength Polypropylene Blends

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Received 10 July 2008; accepted 4 December 2009

DOI 10.1002/app.31928

Published online 2 March 2010 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The aim of this study is the improvement of process stability and film properties of various matrix polymers by the addition of long chain branched (LCB) polypropylene (PP) in the blown film process. Three commercially available PP grades were dry-blended with two different high melt strength (HMS) PP grades with varying weight content in the range of 5, 10, and 20%. Maximum solid output was determined on a Hosokawa blown film line with a film thickness of 50 μm . Thickness was adjusted by proper relation between output and take-up ratio (TUR). The blow-up ratio (BUR) was varied from 1 : 2 to 1 : 3 and 1 : 4 in connection to the output rate and HMS-PP content. Research showed an increase of the output due to the addition of HMS-PP in various matrix polymers and different processing conditions. Influences on mechanical properties related to process parameters concerning stiffness and impact energy were found. Due to

the addition of HMS-PP in a heterophasic PP-copolymer (PP-I) the maximum solid output increases up to 50% as well as tensile properties were enhanced. Stiffness of the blown film is independent of the output and the BUR both in machine direction (MD) and transverse direction (TD). In contrast a reduction of the process stability and solid state properties were determined with homo-PP (PP-H) and random-PP (PP-R) mixtures. Decreasing impact energy of the heterophasic copolymer was determined with increasing HMS-PP content. In comparison to the enhanced stiffness, toughness decreases which refers to a higher brittleness due to the addition of HMS-PP. © 2010 Wiley Periodicals, Inc. *J Appl Polym Sci* 117: 155–162, 2010

Key words: blends; films; mechanical properties; poly(propylene) (PP); processing

INTRODUCTION

Besides the calender- and chill-roll-process, blown film extrusion is the most frequently used processing method for film production in plastics industry. The enormous product range varies from very complex to simple low profit applications. Two of the main criteria for manufacturers are the maximum output rate with a stable process and a consistent performance to meet quality requirements with regard to mechanical and optical properties.^{1,2} These parameters depend on material choice concerning chemical composition, bulk properties, rheological,³ thermal, and mechanical behavior as well as morphological structure development during the manufacturing process.^{4–6} In this context extensional flow is particularly important for film blowing processes and depend on extrusion rates, draw distance as well as

temperature guidance. Comparing the melt strength of various polymers used for blown film leads to an assessment of the optimal extrusion and process parameters.⁷ Polypropylene (PP) as a multipurpose thermoplastic material is established in many different commercial applications. The wide variety of melt flow rates and the compatibility with a multitude of additives and fillers makes it suitable for selective adjustment concerning all processing techniques.⁸ Blown film innovations with PP are still possible, even in the field of well-known applications of flexible and rigid films for packaging.^{9,10} New developments in the design of PP materials concerning process stability, which is comparable with the one of established low-density polyethylene products. These LCB PPs show related strain hardening and melt strength with simultaneous influences on different quality parameters.¹¹ Prospective developments in blown film applications must implicate an optimization in processing and material design. These factors provide high reduction of cost, enhance quality criterias and lead to lower ramp-up times.

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TABLE I
Properties of PP Matrix Resins

Property	Unit	PP-I	PP-R	PP-H
Melt flow rate	g/10 min	0.3	1.9	3.2
Melting temp. (DSC)	°C	167–169	138–140	163–164
Calc. crystallinity (DSC)	%	32	29	40
Calc. CH ₂ content ¹⁶	wt %	w/EPR ^a	~ 5	0
Cryst. temp. (DSC)	°C	109	90	115

^a To be determined by the amount of xylene cold solubles (XCS) and TREF.

In this work the improvement of process stability and solid state blown film properties of various matrix polymers by the addition of long chain branched (LCB) PP are investigated. The aim of this study is to increase the maximum solid output rate up to 50% by the addition of high melt strength (HMS) PP while reaching consistent mechanical properties in the solid blown film. An essential study of Raetzsch et al.¹² describes ways of manufacturing processes for LCB PP and moreover the specific properties for this materials group. Successful applications are found in the area of foaming, thermoforming and extrusion coating.^{13,14} LCB-PP is characterized by a degree of long chain branching of 0.05–0.15 branches/1000C and a polydispersity higher than 4. The biggest advantage with this product class in comparison with linear PPs is strain hardening,¹⁵ increased melt strength and high drawability.

MATERIALS AND METHODS

Mechanical properties and processing parameters are affected by blending different PP polymers with high-melt-strength PPs. The three matrix polymers used in this study were supplied from Borealis Polyolefines, Austria. First is a PP random copolymer (PP-R) and especially developed for biaxial oriented heat shrinkable films. The good processability and mechanical properties make it suitable for food packaging and over wrap applications. Second is a polypropylene homopolymer (PP-H) and employed for manufacturing biaxially oriented PP film. The characteristic good processability on high speed blown film lines in connection with good optical and mechanical properties make it applicable for a wide range of applications in packaging industry. Third is a polypropylene heterophasic copolymer (PP-I), which is suitable for chill-roll and blown-film processes. High tenacity and good mechanical performance are achieved by a reactor blended ethylene-propylene-rubber (EPR) phase. Applications range from food packaging to monoaxial oriented films. The characteristic properties of selected matrix polymers are listed in Table I. HMS-grades are suitable to achieve improved process stability in proc-

esses with high elongational flow. Therefore two different LCB PPs from Borealis Polyolefines (Daploy[®] HMS grades) were used to investigate stability and solid state properties of the polymer blends. A non-commercial polypropylene homo-HMS-PP (H-HMS-PP) with a MFR of 6 g/10min as well as a polypropylene random-HMS-grade (R-HMS-PP) with a MFR of 4 g/10min. The melt flow index was measured according to ISO 1133 with a load of 2.16 kg at 230°C. The degree of crystallinity has been determined from measuring the melt enthalpy (measured via DSC), using the theoretical melt enthalpy at 100% crystallinity of 207.1 J/g.¹⁶ The ethylene-content of the random copolymer PP-R has been estimated according to Gahleitner et al.¹⁷ by measuring melting temperature. The heterophasic copolymer contains a certain amount of EPR which can be identified by measuring xylene cold-insoluble PP-content. Subsequently, the ethylene content is detected by using temperature rising elution fractionation (TREF).

The three matrix polymers were dry-blended at a varying percentages in weight in the range of 5, 10, and 20% with the two HMS-grades and homogenized in a mixing machine. The different films were produced via direct processing on a Hosokawa Alpine HS35HT blown film line with a length to diameter ratio of 18. Screw configuration shows a grooved barrel in the feeding zone, a barrier part and a mixing element. Temperature regulation on the extruder is regulated over three heating tapes (1, 2, and 3) and two cooling fans. Further equipment shows a six channel spiral mandrel and a 60 mm die in the blowing head with a die gap of 1 mm and four tempering adjustments (4, 5, 6, and 7). Outside bubble cooling is supplied over an air ring through an external cooling fan with an inlet for ambient air. Temperature settings were determined in preliminary tests with each polymer and are listed in Table II. The nip speed is unemployable and the haul-off is not vertically adjustable. The design of experiments effects three main parameters, the evaluation of a maximum solid output, the content of LCB HMS-PP and the variation of the blow-up ratio (BUR) for each polymer blend. Film thickness has to

TABLE II
Temperature Settings for Blown-Film Manufacturing

	Temperature settings						
	1	2	3	4	5	6	7
PP-I	200	220	230	240	240	240	230
PP-R	160	180	180	190	190	190	180
PP-H	170	190	190	190	210	210	180

1, feed section; 2, transition section; 3, metering section; 4, head system with filterelement; 5 and 6, spiral mandrel; 7, die.

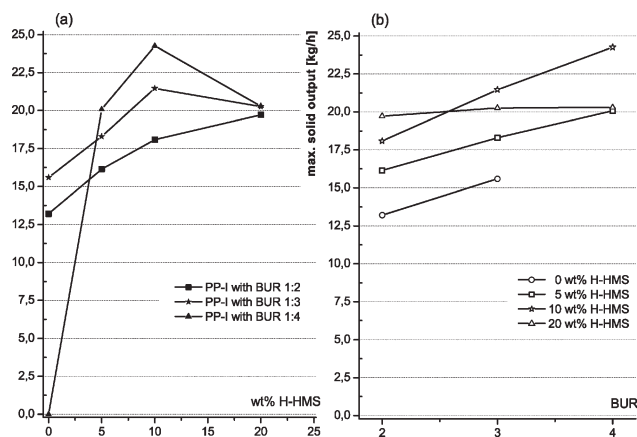


Figure 1 Influences of H-HMS-PP content on max. solid output (a) and BUR (b) in PP-I blends.

be identical at 50 μm whereas the take-up ratio (TUR) was adjusted with increasing output. A deviation variable of 5 μm was defined as measurement tolerances. Quantification of the bubble stability is a difficult matter of identification and depends on a variety of different parameters.^{1,18} The criteria for determination of the maximum solid output for this study is a stable duration of at least 10 min before samples were taken during the running operation.

Beforehand, output variations were detected in screening series at one screw speed. Output variations were consistently detected below 0.1 kg/h and therefore regarded as constant. In light of the experimental setup (single-screw extruder) and the excellent lot consistency of the materials, such minor experimental error is not surprising. No error bar is given in the according charts.

To cover effects on mechanical and processing properties based on varying blow up ratios (BUR), a range of 1 : 2, 1 : 3, and 1 : 4 was set. Amongst others, influences of TUR and BUR on polyethylene films are described in a study from Ganesh-Fard.¹⁸

The collected data from neat materials act as a reference for the evaluation of the maximum solid output. In consideration of material characteristics the frost line height (FLH) has been observed to cause strong effects on process and material properties.^{19,20} The interrelationships between FLH and properties of PP resins blended with LCB HMS-PP were not investigated in this study. FLH was recorded while determining the maximum solid output but was no criterion to abandon an experiment until it reaches 500 mm in height.

Influences due to secondary crystallization were accounted for by storing the samples for minimum 10 days after the production process before acquisition of mechanical properties. Tensile test specimen of the blown film were cut in machine direction (MD) and TD where thickness was measured

through a digital gauge under consideration of the standard testing method ISO527-3. Specimens were tested in a Zwick Z 005 apparatus with a rubberized jaw chuck until yield stress-strain. The free-falling dart drop method was used to represent biaxial stress which can not be measured in an uniaxial tensile test and delivers additional information. Standardized methods depend on different configurations of the instruments. ISO7765-2 is the reference for this test where energy can be directly read because of a load cell integrated in the impact head. Specimens were measured with a Coesfeld apparatus until failure. Breakthrough can occur in local buckling, incipient crack, total crack and brittle fracture. Materials with isotropic behavior show high impact resistance in most cases, while anisotropic film tend to be spitty.

RESULTS AND DISCUSSION

The results in Figure 1 show an increasing output due to the addition of H-HMS-PP on PP-I blends. As an interesting fact process conditions of the neat matrix polymer at a blow up ratio of 1 : 4 were not stable enough to reach the predetermined duration time of 10 min. By raising the amount of H-HMS-PP up to 20 wt % a decrease output can be observed at blow up ratios of 1 : 3 and 1 : 4 in contrast to blends with a BUR of 1 : 2. Visual observation of the bubble during processing displays best cooling efficiency in connection with a BUR of 1 : 3. The highest output in a stable process was given at a loading level of 10 wt % H-HMS-PP and a BUR of 1 : 4.

Blends with PP-R and HMS-PP are displayed in Figure 2. At blow up ratios of 1 : 2 and 1 : 4 the process was hardly effected by bubble cooling and H-HMS-PP content. More comparable conditions could be obtained with an addition of 20 wt % H-HMS-PP on all blow up ratios, whereas max. solid output

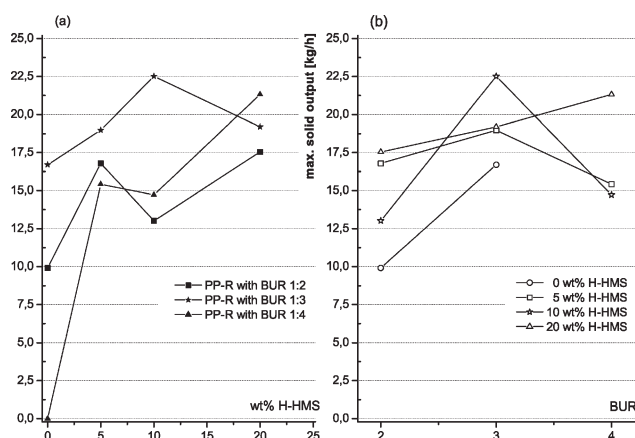


Figure 2 Influences of H-HMS-PP content on max. solid output (a) and BUR (b) in PP-R blends.

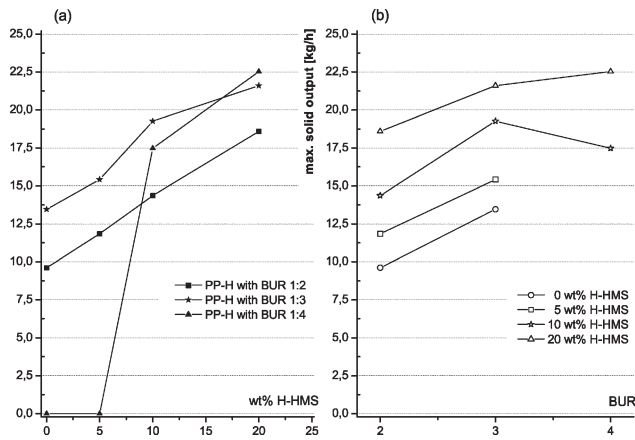


Figure 3 Influences of H-HMS-PP content on max. solid output (a) and BUR (b) in PP-H blends.

showed relations similar to the polymer blends with PP-I. With higher contents of H-HMS-PP and increasing BUR's thickness variations in taken samples were detected. The decrease in throughput is noticeable at a blow up ratio of 1 : 4 of the neat polymer as well as the mixtures with 5 wt % and 10 wt %. Maximum solid output was measured with 10 wt % H-HMS-PP and a BUR of 1 : 3.

Results with varying contents of H-HMS-PP in a PP-H matrix show increasing output at blow up ratios 1 : 2 and 1 : 3 (Fig. 3). With the neat polymer and blends with 5 wt % H-HMS-PP respectively no solid output could be reached at BUR 1 : 4.

Thereby a drastical step up by rising the amount of H-HMS-PP to 10 and 20 wt % takes place, which refers to the high extensibility of LCB PP. The highest max. solid output rates of PP-H blends were determined with 20 wt % mixtures and blow up ratios of 1 : 3 and 1 : 4. Demonstrative for PP-H processing is a higher FLH in accordance to the other polymerblends since bubble cooling leads to helical instabilities.

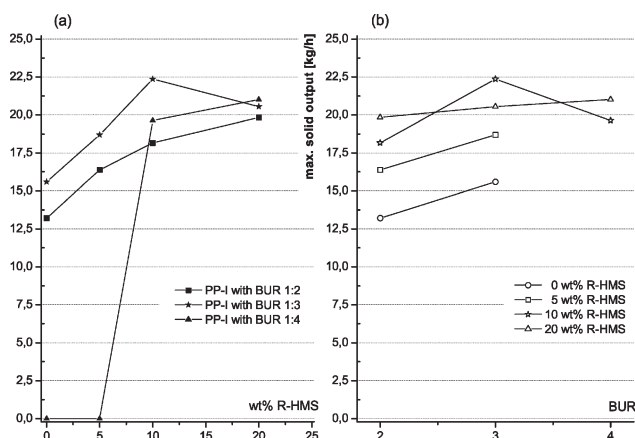


Figure 4 Max. solid output rate of PP-I/R-HMS-PP blends against varying percentage of weight (a) and BUR (b).

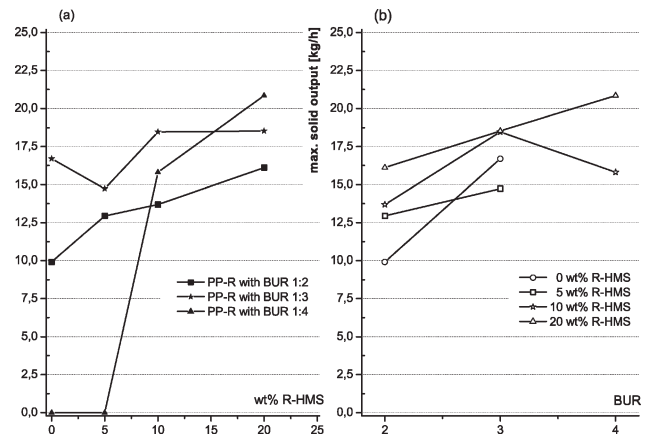


Figure 5 Max. solid output rate of PP-R/R-HMS-PP blends against varying percentage of weight (a) and BUR (b).

Results of processing with blends of PP-I and R-HMS-PP are shown in Figure 4. Maximum solid output increases by the addition of R-HMS-PP besides PP-I blends with 10 wt % and a blow up ratio of 1 : 4. The neat polymer and the mixtures with 5 wt % R-HMS-PP could not be processed under predetermined conditions with a BUR of 1 : 4. However, stability of the process is effected similarly in comparison with H-HMS-PP grades whereas the highest reachable output rate is determined with a proportion of 10 wt % and a BUR of 1 : 3. No noticeable problems occurred by shifting process parameters which indicates a high process stability. Blends with PP-R and R-HMS-PP (Fig. 5) demonstrate a stable process on reaching the 10 wt % R-HMS-PP area. A strong dependence on process conditions with the neat polymer as well as the 5 wt % mixtures are actually given. In comparison to the H-HMS-PP blends no decreasing output could be determined with 20 wt % and a BUR of 1 : 3. The highest solid output can be found with 20 wt % R-HMS-PP and a BUR of 1 : 4. As a matter of fact visual observation of the process shows high interaction with adjusted parameters, therefore cooling adjustment and TUR are of primary interest.

Neat PP-H and blends with 5 and 10 wt % R-HMS-PP display strong effects on cooling rate with blow up ratios of 1 : 4 and therefore no stable output could be achieved. An interesting fact is the decreasing output at a loading level of 5 wt % and blow up ratios of 1 : 2 and 1 : 3 in comparison with the neat polymer (Fig. 6).

Highest possible solid output rates occur with mixtures with 20 wt % which is the same as in results with H-HMS-PP blends.

Maximum solid output could be increased by 6 kg/h with PP-I and PP-R by adding 10 wt % H-HMS-PP with blow up ratios of 1 : 3. Mixtures of 20 wt % H-HMS-PP and PP-H with BUR 1 : 3 actually

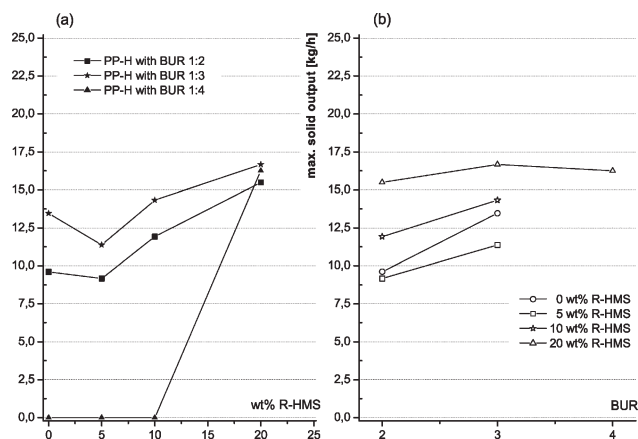


Figure 6 Max. solid output rate of PP-H/R-HMS-PP blends against varying percentage of weight (a) and BUR (b).

show a rising of the output by 8 kg/h. Polymer-blends with R-HMS-PP and blow up ratios of 1 : 3 show an increase of the maximum solid output of PP-I by 7 kg/h, PP-R by 2 kg/h and PP-H by 3 kg/h. Evaluation of the stability showed most stable processing with a percentage of 10% by weight for both HMS-PP grades and blow up ratios of 1 : 3 in accordance to the neat materials, where an increase in production rate of 50% was determined. Nevertheless bubble cooling, FLH, TUR, and BUR are of primary relevance. Furthermore effects of melt rheology and blend compatibility can not be dismissed in accordance to process parameters.

Due to the addition of H-HMS-PP all polymer-blends show an increasing modulus in MD as well as in TD (Fig. 7). The mixtures of PP-H with higher H-HMS-PP content show a more anisotropic behavior than the PP-R blends while the differences between Young's Modulus are significantly high.

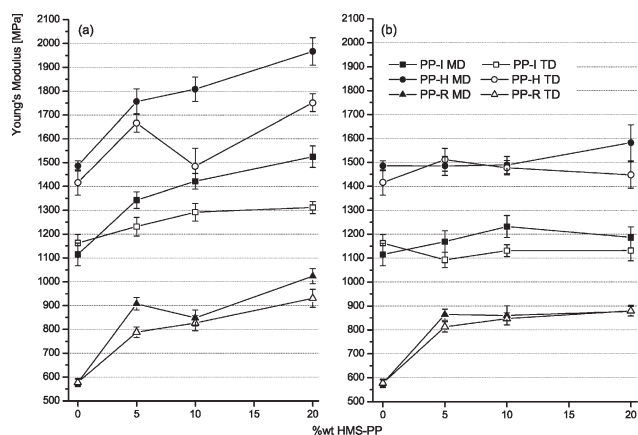


Figure 7 Effects of the HMS-PP content at maximum solid output on the Young's Modulus of 50 μm PP/HMS-PP blended film with a BUR of 1 : 3 in machine direction (MD) and transverse direction (TD). (a) H-HMS-PP and (b) R-HMS-PP.

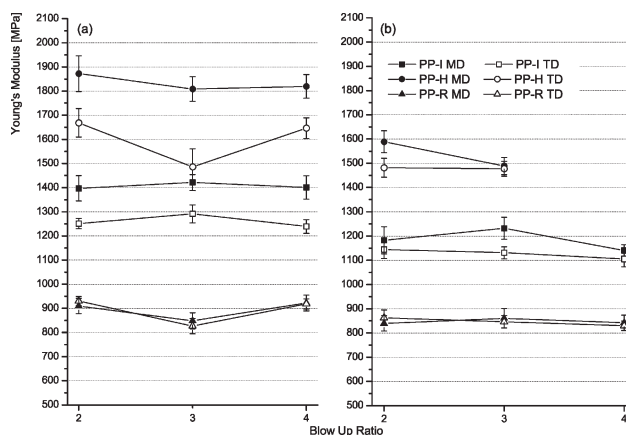


Figure 8 Effects of the BUR at maximum solid output on the Young's Modulus of 50 μm PP/HMS-PP blended film. (a) 10 wt % H-HMS-PP and (b) 10 wt % R-HMS-PP.

This can be explained by the presence of an ethylene phase in the PP-R copolymer which causes different morphological phases in PP and mechanical properties decrease. As can be seen in Figure 7 compounds with PP-I arise consistent and lead to a flat top with increasing H-HMS-PP content while directional properties are as well influenced. Reinforcement of the Modulus increases in accordance to the higher density of entanglements in LCB H-HMS-PP. Measurements with R-HMS-PP are nearly opposite. The blends with PP-I and PP-H do not show any modification regarding to the neat polymer. Comparing these results to H-HMS-PP mixtures, despite of the 5% wt PP-R blends, there is no further reinforcement with increasing R-HMS-PP content neither in MD nor in TD.

Figure 8 shows the dependence of the BUR on the Young's Modulus of the manufactured blown film. Shifting the BUR does not affect the Young's Modulus in all compositions of matrix polymers and both HMS-PP grades. Mixtures with PP-H exhibit a higher anisotropy with H-HMS-PP compared to blends with R-HMS-PP where no maximum solid output could be determined at a BUR of 1 : 4. In general values of PP-I and PP-H blends vary in the area of 200–300 MPa whereas no changes were apparently observed with PP-R mixtures.

Increasing the output with a BUR of 1 : 3 has detrimental effects due to the influence of process conditions where cooling efficiency and therefore FLH as well as the nip speed were located as primary parameters. PP-H blends with H-HMS-PP show a decreasing modulus in both directions which refers to an insufficient bubble cooling (Fig. 9). On the contrary to this the mixtures with R-HMS-PP show strong influences of process parameters compared with helical instabilities of the bubble and therefore maximum solid output could only be measured at two issues. PP-I/H-HMS-PP mixtures show an

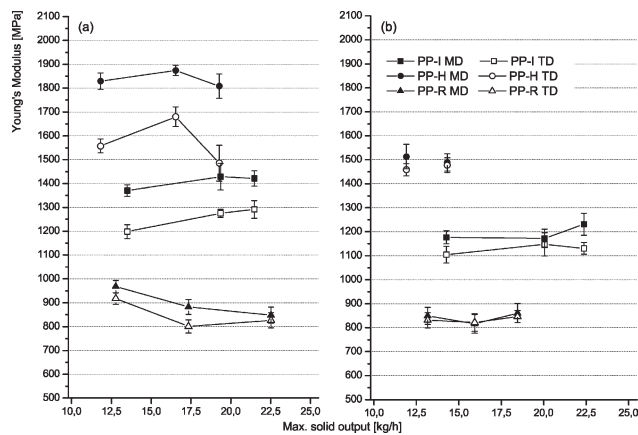


Figure 9 Effects of the maximum solid output on the Young's Modulus of 50 μm PP/HMS-PP blended film with a BUR of 1 : 3 in machine direction (MD) and transverse direction (TD). (a) 10 wt % H-HMS-PP and (b) 10 wt % R-HMS-PP.

increase of the modulus and mixtures of PP-I/R-HMS-PP depict no loss in stiffness compared with an increasing output rate.

Results of tensile tests show that there is a beneficial effect due to an increased loading level of both HMS-PP grades regarding the Young's modulus. Maximum stiffness could be achieved with blends of PP-H and H-HMS-PP whereas the decreasing elongation at yield is disadvantageous. In contrast to this H-HMS-PP in a PP-I matrix provide increased stiffness at same elongation compared to the neat material referring to the embedded EPR-Phase. No considerable effect by varying the BUR occurs but differences between HMS-PP grades were found. The maximum solid output depends on the HMS-PP grade whereas mixtures with PP-I obtain the best process stability. Another aspect was investigated with the dart drop method which performs biaxial stress to the specimen. PP-I blends show a decreasing impact energy with increasing HMS-PP content on both grades, where the R-HMS-PP displays better performance (Fig. 10). *In situ* EPR phase of the block copolymer PP-I leads to a flattening of the curve with R-HMS-PP which refers to the random distributed ethen content. No influence on impact energy could be determined with PP-R and PP-H/H-HMS-PP mixtures. This differs again from R-HMS-PP and PP-R blends that show an increase on impact energy with 5 wt % but maximum solid output remains stable at higher contents.

Figure 11 illustrates the influences of 10 wt % on blow up ratio with maximum solid output. It is visible that the process as well as the HMS-PP grade affects the impact energy.

In detail this means, the differences between PP-I with H-HMS-PP increases impact energy with rising BUR whereas PP-I with R-HMS-PP show an increase

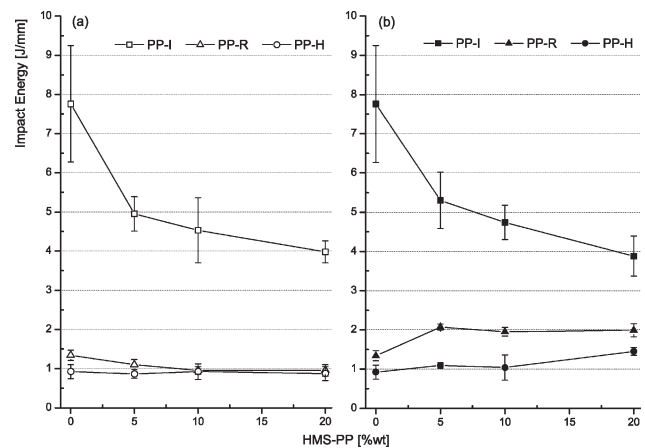


Figure 10 Effects of the HMS-PP content at maximum solid output on the impact energy of 50 μm PP/HMS-PP blended film with a BUR of 1 : 3 with (a) H-HMS-PP and (b) R-HMS-PP.

with blow up ratio of 1 : 3 but no further increase with 1 : 4. The BUR did not show any influence on the impact energy of other blends. In the case of PP-H, no further improvement of the output was possible, therefore no third set of parameters has been able to investigate.

Impact energies of polymerblends with PP-H do not differ in respect to maximum output regardless of the choice of HMS-PP grade (Fig. 12). Mixtures of R-HMS-PP and PP-R show no decrease of impact energy with increasing output rate. Results of H-HMS-PP and PP-I display data values in the range of 3.5 J/mm at about 14 kg/h and 4.5 J/mm at 21 kg/h. Blends with PP-I and R-HMS-PP show constant values on impact energy with higher output rates of about 19 to 22 kg/h. Different structures of PP, referring to statistical distribution or polymers with two or more phases, influence crystallinity and therefore stiffness and flexibility. Furthermore

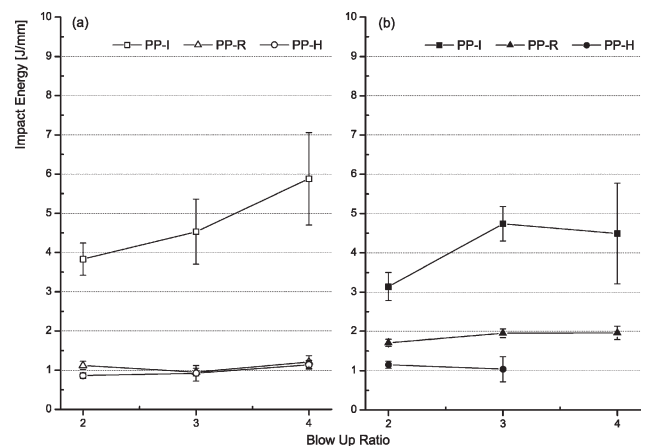


Figure 11 Effects of the BUR at maximum solid output on the impact energy of 50 μm PP/HMS-PP blended film with (a) 10 wt % H-HMS-PP and (b) 10 wt % R-HMS-PP.

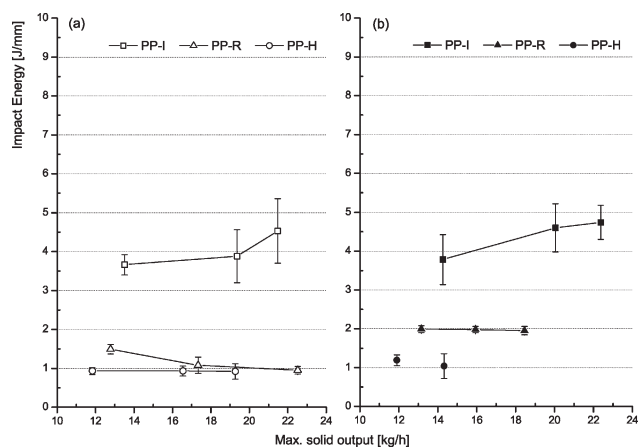


Figure 12 Effects of the maximum solid output on the impact energy of 50 μm PP/HMS-PP blended film with a BUR of 1 : 3 with (a) 10 wt % H-HMS-PP and (b) 10 wt % R-HMS-PP.

chemical composition, arrangement of molecules in the solid state and molecular mass distribution are primary factors for solid state properties. Compatibility of polymers and thermal as well as rheological behavior had major influence during processing. Another aspect which is well-known is epitaxial growth of lamellae due to flow induced crystallization effects and therefore changing on mechanical properties.^{20,21}

Highest reachable output rates could be determined at BURs of 1 : 3 and loading levels of 10 wt % HMS-PP in accordance to the neat polymers (Fig. 13). In comparison BUR's of 1 : 2 as well as 1 : 4 and moreover rising HMS-PP content lead to insufficient cooling and hardly effects processing stability. An interesting fact is the decreasing maximum stable output with higher amounts of HMS-PP.

However, with further increased concentrations of LCB-PP, output rates start to decrease despite fur-

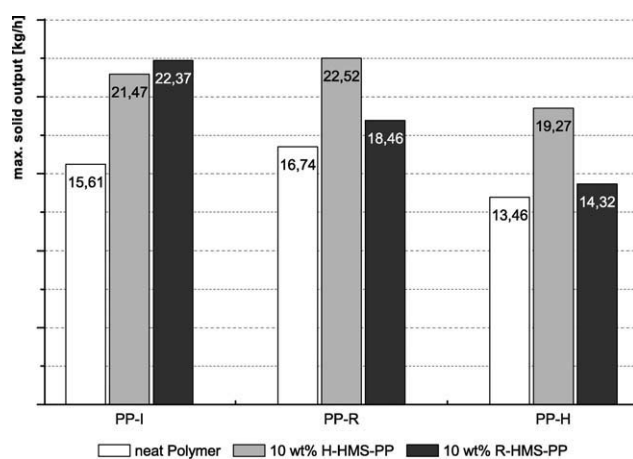


Figure 13 Comparison of the neat polymers and blends with 10 wt % HMS-PP and BUR of 1 : 3 at maximum solid output rate determined.

TABLE III
Comparison of DSC Specific Crystallization Temperature, Enthalpy and Degree of Crystallinity of Neat PP-I and PP-I Blends with 10 wt % H-HMS-PP and R-HMS-PP

HMS-PP grade [-]	HMS-PP content [wt%]	Spec. cryst. temperature [°C]	Spec. cryst. enthalpy [J/g]	Calc. crystallinity $\frac{\Delta H_m}{\Delta H_m^0} \cdot 100$ [%]
None	0	112.2	61.8	32.2
H-HMS-PP	10	122.8	69.6	36.8
R-HMS-PP	10	118.8	64.8	33.2

ther increased melt strength of the systems. This is largely to be interpreted as a result of the increased crystallinity due to the nucleation effect of LCB-PP, expressed in higher crystallization temperature and higher crystallization enthalpy for systems with LCB-PP (Table III). The faster the systems start to crystallize, the more unstable the bubble becomes in the blown film process. In a further relationship, the mechanical properties are connected to the degree of crystallinity, i.e. an increasing degree of crystallinity in a system increases stiffness and reduces toughness.

These two effects, increase of melt strength on the one hand, and increase of crystallinity on the other hand, are working in opposite direction regarding bubble stability. Whilst melt strength has a positive effect, the increase in crystallinity has a negative effect. Therefore, an optimum in bubble stability and output is observed with a medium concentration of HMS-PP.

CONCLUSION

It was found that varying BUR and contents of HMS-PP in different PP-grades have pronounced influences on process stability and mechanical properties. Nevertheless maximum stable output could be enhanced up to 50% due to the addition of HMS-PP in accordance to neat PP-grades.

The main reason for increasing the output rate is the increase of the strain hardening index (SHI) by the addition of HMS-PP-grades. This matter is substantially confirmed with results from Rheotens measurements which show HMS and melt extensibility.^{22,23} Such synergistic effects of melt strength and bubble stability in the blown film process are well-known. Please confer, for example to Ghijssels et al.²⁴ who described the interrelationship between melt strength and bubble stability of mixtures of LCB and linear/short-chain-branched polyethylenes with similar findings. So, the increase in bubble stability with adding small portions of LCB-PP is consistent with the increase in SHI, melt strength and melt extensibility.

Besides the effects on process stability, also mechanical properties are largely influenced by the concentration of HMS-PP in the blends. Results of tensile tests, for example, show an increase of the

Modulus in MD as well as in TD of all matrix polymers by increasing the H-HMS-PP level which corresponds to the higher density of entanglements in this grade.

In comparison, for the polymerblends with R-HMS-PP no further reinforcement could be obtained, neither in MD nor in TD. Shifting the BUR does not affect the Young's Modulus on all compositions of matrix polymers and both HMS-PP grades. As a matter of fact a BUR of 1 : 3 proves as most stable parameter to prevent helical instabilities or draw resonance when increasing the output and nip speed. This is surely in close relationship with processing equipment and therefore cooling rate settings, FLH and nip speed.

Maximum solid output with regard to the stiffness depends on the selected HMS-PP grade. PP-H/H-HMS-PP as an example show the highest modulus but a decreasing elongation at yield. On the other hand PP-I blends with H-HMS-PP provide increased stiffness at the same elongation as the neat polymer. Maximum solid output is a combination of melt and processing temperatures and therefore process depending whereas different melt flow rates and shear thinning are consequences of the blend formulation.

An increase of modulus at given process parameters result from self nucleation effects of long-chain branched PP.¹² Depending on the matrix polymer it is crucial that different morphological phases and degree of entanglements influence crystallinity.²⁵ However, increased crystallization temperatures in the blend formulations indicate nucleating effects and therefore advanced stiffness.

Besides the self-nucleation, also elongation induced crystallization needs to be considered.²⁶ It is known, that the number density of nuclei is a strong function of the specific mechanical work applied to the extended polymer melt. In elaborating the effects of LCB-PP on microscopic level, the polymers introduce strain hardening (HMS) to the melt and enhance strain-induced crystallization during processing. Consequently, the effect of extension to the polymer melt is that the number of nuclei and crystallinity is increased, the film becomes stiffer and more brittle.

Impact energy of PP-I blends decreases with increasing HMS-PP content on both grades. In contrast to this impact energy increases with rising BUR with the exception of PP-I/R-HMS-PP blends with a blow up ratio of 1 : 4. In comparison with maximum solid output, impact energy increases with increasing output but similar to results with BUR 1 : 4 a decrease of the impact energy occurs at highest stable output rate. Mixtures with PP-R and PP-H do not show significant changes on impact behavior despite the addition of HMS-PP, regardless of selected grades.

Formation of tie molecules influence both impact behavior and tensile properties. However, not only the formation of tie molecules but also biaxial orientation during the process affect solid state properties. These effects are more pronounced in a random distributed PP than in a copolymer which results in decreasing growth of lamellae.

Mr. Auinger thank Borealis Polyolefine GmbH for supplying materials and guiding scholarship (Elke Pachner, Peter Nierdersuess). University of Applied Sciences in Wels, Upper Austria, for supervision of the thesis (Gernot Zitzenbacher) and Transfercenter for Plastics Technology in Wels, Upper Austria, for providing the blown film line (Wolfgang Stadlbauer). They also thank all people involved for their outstanding support and teamwork.

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