Biaxial Self-Reinforcement of Isotactic Polypropylene Prepared in Uniaxial Oscillating Stress Field by Injection Molding. I. Processing Conditions and Mechanical Properties

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ABSTRACT: This research explores the longitudinal and latitudinal mechanical properties of injection-molded isotactic polypropylene (iPP) prepared in a uniaxial oscillating stress field by oscillating packing injection molding (OPIM). The methods, processing conditions, and mechanical test results for iPP by conventional injection molding (CIM) and OPIM are described. The mechanical properties in the flow direction (MD) and transverse direction (TD) of the OPIM moldings indicate three types of self-reinforced iPP moldings. The pronounced biaxially self-reinforced iPP specimens exhibit a 55–70% increase of the tensile strength and more than a fourfold increase of the impact strength in the MD, together with more than a 40% increase of the tensile strength and a 30–40% increase of the impact strength in the TD. The OPIM moldings show different stress–strain behavior in the MD and TD. © 2000 John Wiley & Sons, Inc. J Appl Polym Sci 78: 1906–1910, 2000

Key words: isotactic polypropylene; oscillating packing injection molding; biaxial self-reinforcement; uniaxial oscillating stress field; mechanical properties

INTRODUCTION

Many studies have been done on the self-reinforcement of injection-molded polyolefins by using high injection pressure,[1–4] elongational flow during mold filling,[5,6] or successive macroscopic shears to a solidifying melt in the mold.[7–10] Prox and Ehrenstein[4] reported on the self-reinforcement of isotactic polypropylene (iPP) with the application of high injection pressure, high injection speed, and low melt temperature, resulting in a more than 2.5-fold increase of the modulus of elasticity and tensile strength for the self-reinforced iPP compared with the one normally processed. Our previous article[10] reported on the self-reinforcement of iPP by oscillating packing injection molding (OPIM) under low pressure. The Young's modulus and tensile strength had been enhanced from the original 1.4 GPa and 31.0 MPa to 3.0 GPa and 57.8 MPa, respectively. Kalay et al.[7] achieved a 75% increase in the stiffness of iPP following the application of shear-controlled orientation IM (SCORIM). Kalay and Bevis[8] recently reported that an increase of up to 4 times in the impact strength and a substantial increase in the Young's modulus were achieved with SCORIM. And by use of four live-feed arrangement,[8] quasi-isotropic properties of the molded polymer plaques were obtained, exhibit-

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Table I Processing Conditions for Conventional Injection Molding (CIM) at Melt Temperature of 195°C

Specimen No.	Injection Pressure (MPa)	Packing Pressure (MPa)	Mold Temperature (°C)
CIM 1	40	40	20
CIM 2	40	40	40
CIM 3	40	40	60
CIM 4	40	40	80

ing a 74% improvement in the impact failure energy of quadruple live-feed moldings of the PP/ ethylene copolymer PMT6100.

It is almost a rule of thumb that the oriented polymers, such as drawn filaments and uniaxially stretched films, display much higher longitudinal strength and lower latitudinal strength. There are few systematic research studies on the latitudinal strength of oriented injection moldings. When we researched the latitudinal strength of iPP moldings prepared by OPIM, some of them exhibited improvement of mechanical properties in both the flow (MD) and transverse (TD) directions. By controlling the processing parameters, the biaxially self-reinforced iPP specimens were achieved in a uniaxial oscillating stress field by OPIM.

EXPERIMENTAL

Material

The study material was general injection grade iPP homopolymer (1300, Yanshan Petrochemical Corp.) with a melt flow index of 1.1 g/10 min measured at 230°C under 2.16 kg according to ASTM D1238.

Conventional IM (CIM)

To obtain the mechanical properties data of conventional injection-molded iPP specimens for comparison purposes, standard dumbbell-shaped tensile bars (ASTM D638M) and 50 × 6 × 4 mm rectangular impact test bars (GB/T 1043-93) were prepared with a Nissei injection molding machine (model PS40E5ASE). The processing conditions for the CIM are listed in Table I.

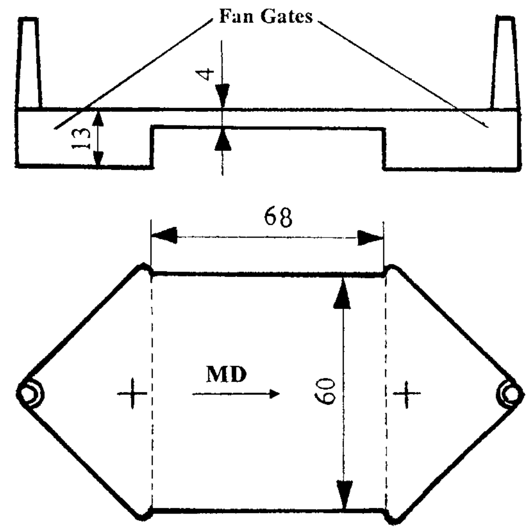

Figure 1 A schematic diagram of the injection-molded plate with the dimensions (mm) as indicated. The locations of the two pressure transducers are indicated by the cross marks.

OPIM

Figure 1 shows a diagram of the injection-molded 68 × 60 × 4 mm plate with two thickened fan gates to ensure uniform flow distribution in the cavity. Two pressure transducers are located at the gates near the plate to monitor the cavity pressure. An SZ 100-g injection molding machine equipped with an OPIM device is used for the production of plates.

The OPIM device (Fig. 2) is a laboratory-scale hot-runner mold with two hydraulic-driven pistons to apply oscillating stress to a solidifying

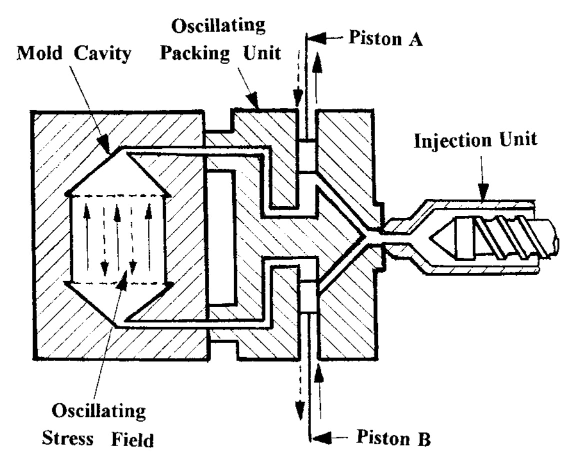

Figure 2 A schematic diagram of the oscillating packing injection molding device. Pistons A and B are operated 180° out of phase.

Table II Processing Conditions for Oscillating Packing Injection Molding (OPIM) At Melt Temperature of 195°C

Specimen No.	Oscillating Packing Pressure (MPa)	Oscillating Frequency (Hz)	Mold Temperature (°C)
OPIM 1-1, 1-2, 1-3	18	0.125, 0.2, 0.5	20
OPIM 1-4, 1-5, 1-6	25	0.125, 0.2, 0.5	
OPIM 1-7, 1-8, 1-9	32	0.125, 0.2, 0.5	
OPIM 2-1, 2-2, 2-3	18	0.125, 0.2, 0.5	40
OPIM 2-4, 2-5, 2-6	25	0.125, 0.2, 0.5	
OPIM 2-7, 2-8, 2-9	32	0.125, 0.2, 0.5	
OPIM 3-1, 3-2, 3-3	18	0.125, 0.2, 0.5	60
OPIM 3-4, 3-5, 3-6	25	0.125, 0.2, 0.5	
OPIM 3-7, 3-8, 3-9	32	0.125, 0.2, 0.5	
OPIM 4-1, 4-2, 4-3	18	0.125, 0.2, 0.5	80
OPIM 4-4, 4-5, 4-6	25	0.125, 0.2, 0.5	
OPIM 4-7, 4-8, 4-9	32	0.125, 0.2, 0.5	

melt in the mold cavity, which is derived from the principles of SCORIM technology that was originally invented by Allan and Bevis.[11] The pistons are set backward initially. As soon as the cavity is simultaneously filled from two gates, the pistons reciprocate in their respective chambers with a phase difference of 180° according to the predetermined oscillating frequencies until the plate is entirely solidified. The processing conditions for OPIM are listed in Table II.

Square plates (60 × 60 × 4 mm) were obtained after the fan gates of the OPIM moldings were cut off. Then the plates were machined to standard dumbbell tensile test bars (ASTM D638M) and 50 × 6 × 4 mm rectangular impact test bars (GB/T 1043-93) along the MD and TD, respectively.

Tensile Testing

A Shimadzu universal testing machine (model AG-10TA) was used for tensile testing at room temperature (23°C). The crosshead speed was 50 mm/min.

Impact Testing

The CIM and OPIM (in MD and TD) impact testing bars were notched to C type by a single-tooth cutter according to GB/T1043-93. A Charpy-type impact machine was used to determine the impact strength of CIM and OPIM specimens at room temperature (23°C). The impact speed was 2.9 m/s.

RESULTS AND DISCUSSION

Mechanical Properties of CIM Specimens

The mechanical test results of CIM specimens are shown in Table III. With the mold temperature increasing from 20 to 80°C, the tensile strength increases slightly whereas the elongation at break decreases substantially, because the degree of crystallinity increases with increasing mold temperature.[12] The impact strength showed little dependence on the mold temperature.

Mechanical Properties of OPIM Specimens

The mechanical properties of OPIM specimens exhibit interesting experimental evidence that some are reinforced in both the MD and TD (i.e., biaxial self-reinforcement) and others are only reinforced in the MD (i.e., uniaxial self-reinforcement). According to the degree of biaxial self-reinforcement of the OPIM moldings compared

Table III Mechanical Properties of Conventional Injection Moldings (CIM)

Specimen No.	Tensile Strength (MPa)	Strain at Break (%)	Impact Strength (kJ/m^2)
CIM 1	31.04	435.3	2.14
CIM 2	31.63	324.8	2.09
CIM 3	32.07	108.5	2.12
CIM 4	32.29	70.3	2.16

Table IV Mechanical Properties of Oscillating Packing Injection Moldings (OPIM)

Specimen Type	Specimen No.	Tensile Strength (MPa)		Strain at Break (%)		Impact Strength (kJ/m^2)	
		MD	TD	MD	TD	MD	TD
A	OPIM 1-9	51.47	43.71	42.5	23.3	11.68	2.83
	OPIM 2-9	51.56	45.32	33.1	18.6	10.84	3.02
	OPIM 3-9	49.74	44.93	34.5	18.9	12.54	3.05
	OPIM 4-9	55.16	45.32	48.4	18.9	11.23	2.87
B	OPIM 1-6	45.14	44.51	33.2	19.7	7.32	2.38
	OPIM 2-8	43.45	44.96	46.6	17.0	8.28	2.43
	OPIM 3-6	44.56	43.99	37.8	23.6	7.48	2.35
	OPIM 4-8	46.87	43.71	60.1	21.8	9.02	2.38
C	OPIM 1-7	57.57	35.17	38.9	19.4	12.09	1.67
	OPIM 2-7	50.71	36.57	41.9	16.3	9.83	1.65
	OPIM 3-8	57.16	35.82	37.9	13.8	12.21	1.71
	OPIM 4-4	53.53	36.60	40.8	18.1	10.46	1.73

with the CIM moldings at the same mold temperature, the self-reinforced OPIM specimens can be classified into three types.

1. Type A are pronounced biaxially self-reinforced iPP specimens. In the MD there is about a 55–70% increase of the tensile strength and more than a 400% increase of the impact strength. In the TD there is more than a 40% increase of the tensile strength and about a 30−40% increase of the impact strength.
2. Type B are biaxially self-reinforced iPP specimens. In the MD there is about a 40% increase of the tensile strength and about a 300% increase of the impact strength. In the TD there is about a 40% increase of the tensile strength and about a 10% increase of the impact strength.
3. Type C are uniaxially self-reinforced iPP specimens. In the MD there is more than a 70% increase of the tensile strength and more than a 400% increase of the impact strength. In the TD there is about a 10% increase of the tensile strength and about a 20% decrease of the impact strength.

The mechanical properties data of the typical specimens of these three types are summarized in Table IV.

In analyzing the mechanical properties (Table IV) and the processing conditions (Table II) for the OPIM moldings, we found that the oscillating packing pressure is the dominant processing parameter for self-reinforcement in the MD and TD, especially in the MD. As for the OPIM moldings under 32-MPa oscillating packing pressure, a higher oscillating frequency (0.5 Hz) results in substantial increases of the mechanical properties in the TD. It seems that the mold temperature has little influence on the tensile strength and impact strength of OPIM moldings.

Stress–Strain Curves

Figure 3 illustrates the stress–strain curves of CIM and OPIIM (in the MD and TD) specimens.

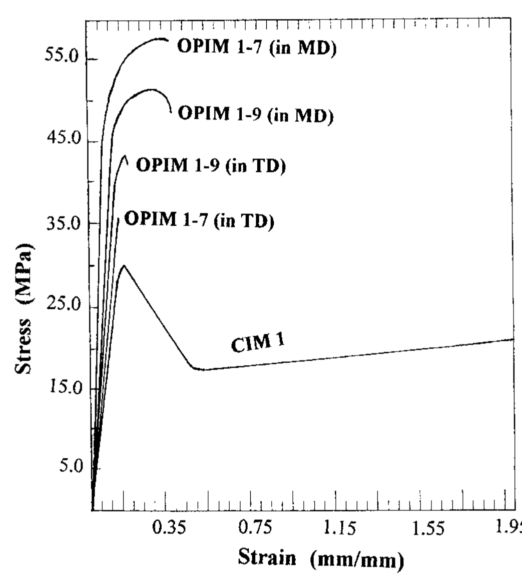

Figure 3 The stress–strain curves for CIM 1, OPIM 1-7 (in MD and TD), and OPIM 1-9 (in MD and TD).

The CIM molding shows a lower tensile strength at yield with distinct necking and large elongation. The highest tensile strength of 57.58 MPa at yield and 38.9% strain at break are obtained for OPIM 1-7 (classified as C type) in the MD. The OPIM 1-7 in the TD displays nearly Hooken behavior up to fracture with 35.17 MPa at peak (break) and 19.4% strain at break. OPIM 1-9 (classified as A type) shows 51.47 MPa and 42.5% strain at break in the MD, together with a 43.71-MPa stress at peak and 23.3% strain at break in the TD. The OPIM specimens in the TD exhibit typical brittle break. The OPIM specimens in the MD have obvious yield points and about 40% strain at break, showing relative ductile breaks in comparison to that in the TD. The stress–strain curves show that the OPIM moldings are anisotropic, because of the formation of an interlocking shish-kebab morphology in the outer shear region as discussed in detail in a subsequent article.[13]

CONCLUSIONS

Under some specific processing conditions, biaxially self-reinforced iPP specimens can be achieved in a uniaxial oscillating stress field from the application of OPIM. For the pronounced biaxially self-reinforced iPP specimens, the tensile strength and impact strength increase substantially in the MD and TD. Higher oscillating packing pressure and higher oscillating frequency result in greater biaxial self-reinforcement of OPIM iPP moldings. The influence of the mold temperature seems to be weak. The OPIM moldings are anisotropic, exhibiting different stress–strain behavior in the MD and TD.

REFERENCES

1. Djurner, K.; Kubat, J.; Rigdahl, M. Polymer 1977, 18, 1968.
2. Kubat, J.; Manson, J.-A. Polym Eng Sci 1983, 23, 869.
3. Kubat, J.; Manson, J.-A.; Rigdahl, M. Polym Eng Sci 1983, 23, 877.
4. Prox, M.; Ehrenstein, G. W. Kunststoffe 1991, 81, 1057.
5. Bayer, R. K.; Zachmann, H. G.; Balta Calleja, F. J.; Umbach, H. Polym Eng Sci 1989, 29, 186.
6. Lopez Cabarcos, E.; Bayer, R. K.; Zachmann, H. G.; Balta Calleja, F. J.; Meins, W. Polym Eng Sci 1989, 29, 193.
7. Kalay, G.; Allan, P. S.; Bevis, M. J. Plast Rubber Compos Process Applic 1995, 23, 71.
8. Kalay, G.; Bevis, M. J. J Polym Sci Polym Phys Ed 1997, 35, 241.
9. Guan, Q.; Shen, K.; Ji, J.; Zhu, J. J Appl Polym Sci 1995, 55, 1797.
10. Guan, Q.; Zhu, X.; Chiu, D.; Shen, K.; Lai, F. S.; Mccarthy, S. P. J Appl Polym Sci 1996, 62, 755.
11. Allan, P. S.; Bevis, M. J. U.K. Pat. 2,170,140B, Eur. Pat. EP 0,188,120B1, U.S. Pat. 4,925,161 (1986).
12. Murphy, N. W.; Thomas, K.; Bevis, M. J. Plast Rubber Compos Process Applic 1988, 9, 3.
13. Chen, L.-M.; Shen, K. J Appl Polym Sci, to appear.