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High-Density Polyethylene/Kaolin Clay Composites: Optimiztion of The Injection Moulding Process Parameters Towards Minimum Shrinkage and Warpage

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Abstract

Optimization of the injection moulding process parameters of thermoplastic composites made of high-density polyethylene (HDPE) and kaolin clay (KC) was carried out using the Taguchi method. The parameters that were taken into consideration were melting temperature, packing pressure and packing time. Composites containing 98 wt% of HDPE and 2wt% of KC with various particle sizes of <75, 75-106 and 106-150 µm were used. Two defects that are usually associated with the injection moulding process of polymers were selected, namely shrinkage and warpage. Results showed that the optimal parameters needed to obtain a minimum shrinkage value for composites containing clay (regardless of its particle size) are very similar to those for the pure HDPE. Contrary, the optimal parameters needed to obtain a minimum warpage value depends on the size of clay particles added, which were also different from those of the pure HDPE. Results also revealed that the most effective parameter (both shrinkage and warpage) for pure HDPE and its composites with clay was the melting temperature.

Keywords: Clay, High Density Polyethylene, Injection Moulding, Shrinkage and Warpage

INTRODUCTION

Clay particles are highly recognized as fillers and are extensively utilized in polymer composites owing to their exceptional properties. [1-3]. These properties include cation exchange capabilities, swelling behaviour, plastic behaviour when wet, ability to harden when dried or fired and low permeability. Composite materials obtained from the combination of polymers and clays possess a unique set of properties that make them highly desirable for various industrial applications. These materials offer enhanced stiffness, improved strength, high impact resistance, and thermal stability, making them ideal for use in automobiles, electrically conductive materials, and other applications where such properties are needed. [4] The injection moulding process is widely used in the manufacturing of industrial parts made from polymers and polymer composites. This process involves injecting melted polymeric materials into a mould to create the desired shape. This process depends on a variety of variables, such as melting temperature, injection pressure, filling time. Although the process is considered to be very stable, however, due to some internal interactions of several parameters, the resultant product's quality could be dramatically affected. Thereafter, this process requires optimization, which could improve the physical and mechanical properties of the final products.

It has been shown that optimizing the injection moulding processing parameters can be performed via several techniques [5]. Nowadays, computer-aided simulations and statistical experimental approaches can be used to achieve the required factors to obtain optimal processing conditions. Taguchi method is one of the leading statistical methods for the optimization of injection moulding processes. This method has been recently used for optimizing the processing parameters of a variety of polymers that could be injection moulded such as polyethylene [6-8], polypropylene (PP) [9, 10], recycled high-density polyethylene (HDPE) [11], acrylonitrile butadiene styrene copolymers [12], polycarbonate [13], polybutylene terephthalate [14], polyamide [15], polyurethane [16], and polystyrene [17]. Optimizing the injection moulding process of polymer composites using the Taguchi method was also under investigation. For instance, high-density polyethylene (HDPE)/TiO_2 nanocomposites were studied using this technique, where four parameters were chosen; concentration of TiO_2, barrel temperature, residence time and packing time, while mechanical properties such as yield strength, modulus of elasticity and elongation were selected as representative performance [18]. The authors found that 5wt % TiO_2, 225 ^oC barrel temperature, the residence time of 30 min and packing time of 20 seconds were found to be the optimal operating variables.

Optimization of ultrasonic injection moulding for ultra-high molecular weight polyethylene/graphite composites was also studied by the Taguchi method [19]. The authors showed that the optimal parameters to maximize the tensile strength of the composites were the mould temperature, which was the most significant parameter, followed by the graphite content. Kamaruddin et al. [20] utilized this technique to improve the quality characteristic of products made by injection moulding to reduce the shrinkage of polymer blends of PP (75%) and low density polyethylene (LDPE) (25%). Their findings showed that combination of low melting temperature, high injection pressure, low holding pressure, long holding time and long cooling time affected the shrinkage of the final product. Similarly, Mehat et al. [21] carried out a study to improve the mechanical properties of blends of recycled and virgin plastics via optimal processing parameters using the Taguchi method. Four controllable factors were chosen, which included melting temperature, injection pressure, injection time and filling time each at three levels. The results revealed that the products, which are made of 25% recycled PP and 75% virgin PP exhibited a better flexural modulus compared to the virgin PP.

Rajesg et al. [22] studied the effect of injection moulding parameters on the nanofiller dispersion of PP/clay nanocomposites. The major individual influencing parameter was the injection flow rate, which improved the nanoclay dispersion with the combination of high back pressure and high screw rotational speed. Polypropylene composites containing clay and natural fibres were also studied. Othman et al. [23-25] used polypropylene mixed with clay and fibres obtained from bamboo trees in their optimization study of processing conditions using the injection moulding method. According to them, the optimum parameters used to obtain a minimized shrinkage value were melting temperature of 170 ^oC, the pressure of 80%, and screw speed of 70% and 3 seconds of filling time. Whereas, minimum warpage was obtained when they used melting temperature of 170 ^oC, the pressure of 70%, screw speed of 70% and 2 seconds of filling time.

In a recent study carried out by our group [26], we investigated the effect of Libyan kaolin clay on the impact strength of HDPE. Our results showed that 2wt% kaolin clay added to HDPE enhanced its impact resistance up to 33% compared to virgin HDPE. Another study [27] showed the particle size of kaolin clay has a significant effect on the mechanical properties of HDPE composites. Clay particles sizes of 75-150 µm appear to have better overall properties compared to composites containing clay particles with sizes of <75 and > 150 µm. Anova studies carried out on the same composites have shown the effect of injection temperature on shrinkage of composites with particle sizes <75 and 106-150µm was statistically significant. Also, the injection temperature has an effect on the impact strength of the composites with particle sizes <75 and 106-150µm was clear. [28] In this study, the attempt to investigate the optimization of the injection moulding process parameters of these composites was carried out. Taguchi method was used to help evaluate the best injection moulding parameters that produced the minimum shrinkage and warpage using clay with different particle sizes. Three factors, melting temperature, packing pressure and packing time and their effect on shrinkage and warpage was investigated using the Taguchi method.

EXPERIMENTAL

Materials

HDPE was used as received as the matrix polymer (SABIC Saudi Arabia, HDPE F00952, melt flow index 0.05 g/10 min and density 952 g/cm^3). Kaolin clay was supplied by Industrial Research Center in Tripoli-Libya (collected from Sabha city in Libya). It was sieved to remove impurities and then passed through different sieve sizes to get particle sizes of (<75, 75-106 and 106-150 µm).

Composite preparation

kaolin clay was dried in an air circulating oven at 85 °C for 24 hr and mixed with the polymer in (Ultra centrifugal mill ZM 200 -RETSCH) to obtain a very fine powder of the mixture. The final mixing was then carried out by melt mixing method using twin-screw extruder (Brabender, Germany) at a screw speed of 35 r.p.m. and L/D ratio of 48 at the temperature range of 160-200 °C. The temperature setup of the extruder is shown in) Table 1)The extruded composites were cooled in air and then ground. Samples for shrinkage and warpage measurements were prepared in an injection moulding machine (Xplore 12ml, Netherlands) at the various injection temperature, packing pressure and packing times.

Table (1): Temperature setup of the extruder

Zone No.	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Temp (°C)	160	170	170	180	190	200

Shrinkage measurements

Shrinkage refers to the decrease in size that occurs in a linear direction when a polymeric object cools down to room temperature after being injected at molding temperature. To obtain the shrinkage value (S), three measurements are taken for each trial, and the following equation is used.

$$S = \frac{L_c - L_{ave}}{L_c}$$

Where, Lc is the actual mould cavity length (mm) and L_{ave} is the average of sample length (mm). The actual mould cavity length (Lc) is calculated as: $Lc = L\ [1+\alpha\ (T_{mould}-T_{ambient})]$

Where, α is the coefficient of thermal expansion for steel (6.45×10^{-6} 1/°F), L is the measured cavity length (mm), T_{mould} is the mould temperature in °F, and $T_{ambient}$ is ambient temperature in °F.

Warpage measurements

The thickness of the sample was measured at three different places by using a digital micrometre. Three measurements for each trial were taken, and the average warpage value was used. The warpage (Z) was calculated using the following formula:

$$Z = h - t_a$$

Where, h is the depth of the mould cavity (mm) and t_a is the average of sample thickness (mm).

Design of Experiment

Taguchi method with $L_9 3^3$ orthogonal array using the statistical software Minilab-19 was adopted and used in this study. The injection moulding parameters were investigated are melting temperature, packing pressure and packing time. These factors were set at three levels for three different composites containing different clay particle sizes (<75, 75-106 and 106-150 µm) as shown in) Table 2). In this study, the smaller value of shrinkage and warpage should give a better quality characteristic of the final product. Therefore, the "smaller is better" options as signal to noise ratio (S/N) was used. (Table 3) shows the details of the orthogonal array used for the Taguchi study.

Table (2): Injection moulding parameters, factor symbols and their level selection.

Parameters	Unites	Factor symbol	Level 1	Level 2	Level 3
Injection temperature (NT)	(°C)	A	180	200	220
Packing pressure (PP)	(Bar)	B	6	8	10
Packing time (PT)	(Sec)	C	1	2	3

Table (3): Taguchi method $L_9 3^3$ orthogonal array

Trial No	A (NT)	B (PP)	C (PT)
1	1 (180)	1 (6)	1 (1)
2	1 (180)	2 (8)	2 (2)
3	1 (180)	3 (10)	3 (3)
4	2 (200)	1 (6)	2 (2)
5	2 (200)	2 (8)	3 (3)
6	2 (200)	3 (10)	1 (1)
7	3 (220)	1 (6)	3 (3)
8	3 (220)	2 (8)	1 (1)
9	3 (220)	3 (10)	2 (2)

RESULT AND DISSECTION

The focus of the study was to investigate the effect of injection moulding process parameters on some defects of parts made from HDPE/kaolin clay composites namely shrinkage and warpage. The Taguchi approach was utilized to optimize the injection process of such composites towards a minimum shrinkage and warpage. Three different clay particle sizes were used, and their effect on the optimization process was also discussed. For comparison, the optimization of pure HDPE was also studied. A confirmation test based on experimental trials was carried out. (Table 4) shows the average shrinkage and warpage values for pure HDPE and all composites (containing clay with different particle sizes) based on each trial.

Table (4): The average shrinkage and warpage for different composites with different particle sizes

Trial No	Pure HDPE		75 µm particles size		106 µm particles size		150 µm particles size	
	Shrinkage	Warpage	Shrinkage	Warpage	Shrinkage	Warpage	Shrinkage	Warpage
1	0.026	0.14	0.021	0.06	0.051	0.02	0.051	0.05
2	0.009	0.14	0.014	0.04	0.042	0.04	0.041	0.04
3	0.008	0.14	0.022	0.05	0.053	0.04	0.053	0.11
4	0.025	0.14	0.032	0.06	0.061	0.07	0.063	0.05
5	0.017	0.10	0.023	0.07	0.056	0.05	0.055	0.05
6	0.041	0.10	0.032	0.04	0.067	0.07	0.063	0.07
7	0.029	0.07	0.032	0.04	0.059	0.06	0.056	0.07
8	0.035	0.14	0.032	0.04	0.070	0.06	0.063	0.06
9	0.025	0.07	0.035	0.06	0.057	0.02	0.062	0.06

Based on the results achieved in) Table 4), the value for a signal to noise (S/N) ratio was calculated and used to measure the quality characteristic of the sample. In this study, the smaller values of shrinkage and warpage shall give a better quality characteristic. Therefore, the option “smaller is better” was used. The response values of the S/N ratio for shrinkage and warpage for pure HDPE and all composites containing clay of different particle sizes of <75, 75-106 and 106-150 µm are shown in) Tables 5-8).

Table (5): The response values of S/N ratio for shrinkage and warpage for pure HDPE

HDPE	Level	NT		PP		PT	
		Shrinkage	Warpage	Shrinkage	Warpage	Shrinkage	Warpage
---	1	37.67	17.08	31.36	19.08	29.31	18.05
---	2	31.54	18.05	34.77	18.05	34.70	19.08
---	3	30.56	20.06	33.64	20.06	35.76	20.06
Delta	--	7.11	4.01	3.41	2.01	6.44	2.01
Rank	--	1	1	3	2.5	2	2.5

Table (6): The response values of S/N ratio for shrinkage and warpage for composites containing clay particle size of <75 µm

Clay particle size (µm)	Level	NT		PP		PT	
		Shrinkage	Warpage	Shrinkage	Warpage	Shrinkage	Warpage
<75	1	34.31	26.14	30.94	25.61	30.97	26.78
<75	2	30.6	25.16	32.86	26.34	31.68	25.61
<75	3	29.39	26.78	30.51	26.14	31.65	25.69
Delta	--	4.93	1.62	2.35	0.73	0.71	1.17
Rank	--	1	1	2	3	3	2

Table (7): The response values of S/N ratio for shrinkage and warpage for composites containing clay particle size of 75-106 µm

Clay particle size (µm)	Level	NT		PP		PT	
		Shrinkage	Warpage	Shrinkage	Warpage	Shrinkage	Warpage
75-106	1	26.26	29.13	24.87	26.34	24.14	26.34
75-106	2	24.22	24.07	25.2	26.14	25.53	27.90
75-106	3	24.18	27.17	24.58	27.90	24.98	26.14
Delta	--	2.08	5.06	0.63	1.76	1.39	1.76
Rank	--	1	1	3	2.5	2	2.5

Table (8): The response values of S/N ratio for shrinkage and warpage for composites containing clay particle size of 106-150 μm

Clay particle size (μm)	Level	NT		PP		PT	
		Shrinkage	Warpage	Shrinkage	Warpage	Shrinkage	Warpage
106-150	1	26.24	24.30	24.87	24.78	24.55	24.52
106-150	2	24.35	25.05	25.57	26.14	25.22	26.14
106-150	3	24.33	23.73	24.48	22.15	25.15	22.41
Delta	--	1.91	1.32	1.09	3.99	0.67	3.73
Rank	--	1	3	2	1	3	2

Graphs of main effects plots for S/N ratio for shrinkage and warpage values for pure HDPE and various composites are shown in) Fig 1-4).

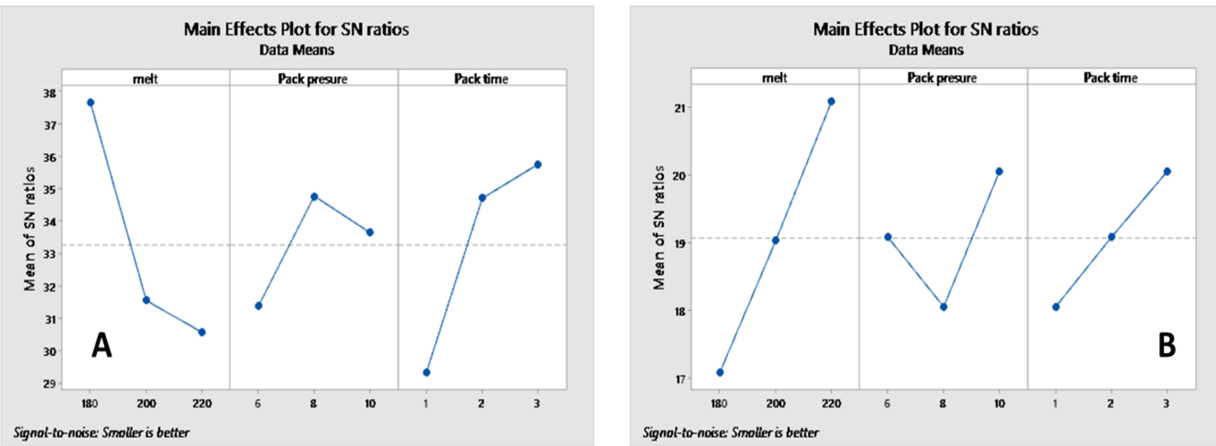

Figure (1). S/N ratio response for pure polymer a) shrinkage and b) warpage.

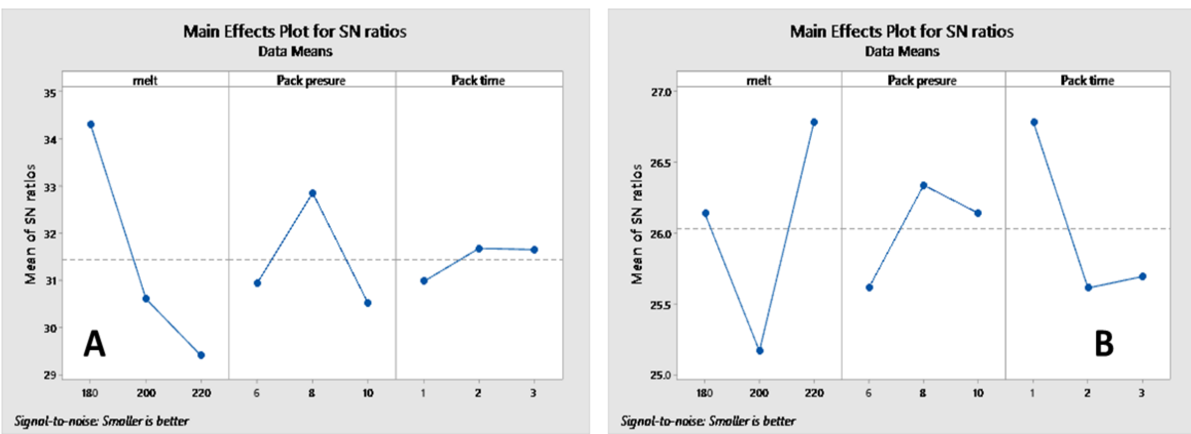

Figure (2). S/N ratio response for composite with clay particle size of <75 μm: a) shrinkage and b) warpage.

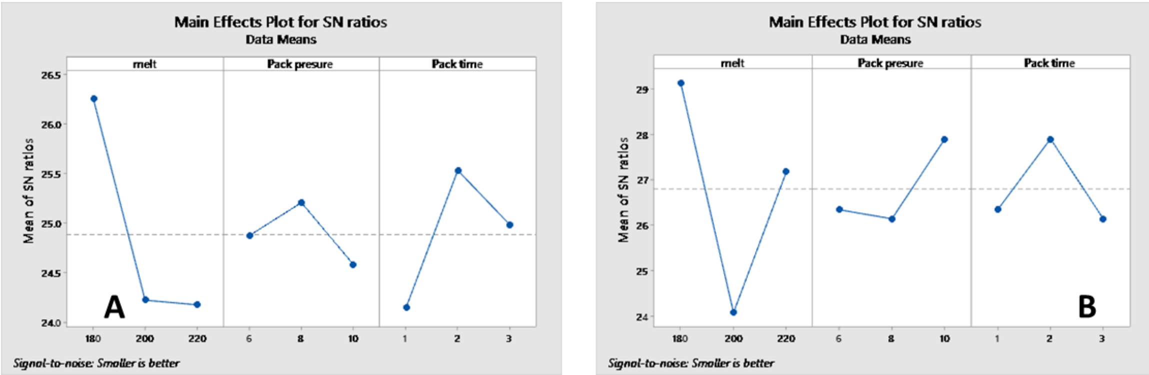

Figure (3). S/N ratio response for composite with clay particle size of 75-106 μm: a) shrinkage and b) warpage.

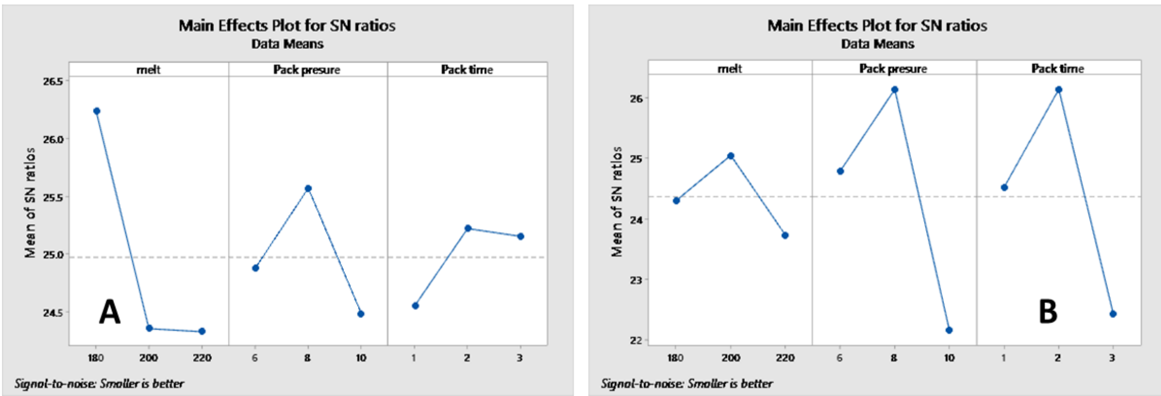

Figure (4). S/N ratio response for composite with clay particle size of 106-150 μm: a) shrinkage and b) warpage.

The best conditions can be determined by selecting the level with the highest response value for each factor. Based on these results, the best conditions that were used to obtain the least shrinkage and warpage values for pure HDPE and each composite were selected, which are summarized in (Table 9).

Table (9): The optimal combination of conditions for minimizing shrinkage and warpage

Clay particle size (μm)	NT		PP		PT	
	Shrinkage	Warpage	Shrinkage	Warpage	Shrinkage	Warpage
No clay	37.67	20.06	34.77	20.06	35.76	20.06
Level	1	3	2	3	3	3
<75	34.31	26.78	32.86	26.34	31.68	26.78
Level	1	3	2	2	2	1
75-106	26.26	29.13	25.2	27.9	25.53	27.9
Level	1	1	2	3	2	2
106-150	26.24	25.05	25.57	26.14	25.22	26.14
Level	1	2	2	2	2	2

As shown in (Table 9), one can see that the optimal conditions for all composites containing clay with various particle sizes are the same for shrinkage, which was at the factor levels of A1, B2, C2. This indicates that the size of clay particles has no significant effect on the injection moulding factors studied. In addition, results showed that the conditions for all composites are slightly different from those for the pure HDPE (A1, B2, and C3). On the other hand, the size of clay particles seems to have a significant effect on the warpage values. For composites with the clay particle size of <75 μm, a minimum warpage value was obtained at levels of A3, B2, C1. For composites with the clay particle size of 75-106 µm, the best combination of factors was obtained at levels A1, B3, C2, while composites with the clay particle size of 106-150 µm, the best combination of factors were at levels A2, B2, C2. Furthermore, the optimal conditions for pure HDPE were at levels A3, B3, C3, which are different from those for the composites. These variations indicate that the size of clay particles has a significant influence on the injection moulding process parameters under study.

Confirmation test

Confirmation tests were carried out using the best combination of conditions obtained from the Taguchi study, which resulted in the minimum shrinkage and warpage values. The test was carried out for composites only at a different. (Table 10) shows the experimental shrinkage and warpage values for all composites with various clay particle sizes.

Table (10): Shrinkage and warpage values for composites containing clay with varies particle sizes.

Defect name	Clay particle size of <75 µm	Clay particle size of 75-106 µm	Clay particle size of 106-150 µm
Shrinkage	0.016	0.018	0.015
Warpage	0.020	0.050	0.040

(Table 10) clearly shows that the shrinkage and warpage values for all composites are relatively small, similar to the values obtained at the optimization levels. The results confirm that the optimal conditions found by the Taguchi study indeed produced the minimum value of shrinkage and warpage. Taguchi's results showed the lowest shrinkage value for composites with different clay particle sizes obtained was at levels A1, B2, C2 with values between 0.015-0.018. Similarly, Taguchi results showed the lowest warpage value for composite with the clay particle size of <75 at levels A3, B2, C1. For composite with the clay particle size of 75-106 µm, the lowest warpage value was obtained at levels A1, B3, C2. For composite with the clay particle size of 106-150 µm, the lowest warpage value was obtained at levels A2, B2, C2. The warpage value between obtained were 0.02-0.05 for composites with various clay particles, which were very close to the optimal values obtained above.

CONCLUSION

Taguchi method was used to study the optimal injection moulding process parameters for composites containing high-density polyethylene (HDPE) and Kaolin clay (KC). This was carried out to predicate the best possible combination of conditions in order to minimize the shrinkage and warpage of parts made from these composites. The following can be concluded from this study:

- The optimum conditions for a minimum shrinkage

The optimal combination of parameters that gave minimum shrinkage for pure HDPE is injection temperature of 180 °C, packing pressure of 8 bar and 3 sec of packing time. Those for composite containing KC with particle sizes of <75, 75-106 and 106-150 µm are injection temperature of 180 °C, packing pressure of 8 bar and 2 sec of packing time. The most effective parameter for pure HDPE and all composites containing clay particles of <75, 75-106 and 106-150 µm is injection temperature.

- The optimum conditions for a minimum warpage

The optimal combination of parameters that gave minimum warpage for pure HDPE are injection temperature of 220 °C, packing pressure of 10 bar and 3 sec of packing time Those for composite containing KC with the particle size of <75, 75-106 and 106-150 µm are injection temperature of 180 °C, packing pressure of 8 bar and 1 sec of packing time, injection temperature of 180 °C, packing pressure of 10 bar and 2 sec of packing time and injection temperature of 200 °C, packing pressure of 8 bar and 2 sec of packing time, respectively. The most effective parameter for pure HDPE and composites containing clay particles of <75 and 75-106 µm is the injection temperature, while the most effective parameter for composites containing clay particle size of 106-150 µm is the packing pressure.

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