Composites: Part A 83 (2016) 152–159

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Sisal-glass fiber hybrid biocomposite: Optimization of injection molding parameters using Taguchi method for reducing shrinkage

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ARTICLE INFO

Article history:
Available online 30 October 2015

Keywords:
A. Biocomposites
B. Defects
C. Injection molding
C. Statistical methods

ABSTRACT

The current work presents an application of Taguchi method to optimize injection molding (IM) process parameters of sisal-glass fiber hybrid biocomposite. Six parameters that influence flow and cross-flow shrinkage such as injection pressure, melt temperature, mold temperature, holding pressure, cooling time and holding time were selected as variables and two hybrid biocomposites were used with different content of sisal (SF) and glass fiber (GF); SF20GF10 and SF10GF20. For the experimental design, L18 orthogonal array with a mixed-level design and signal-to-noise (S/N) of smaller-the-better was used. Optimal combination IM parameters were determined and the significant variables were identified using ANOVA. Optimized flow and cross-flow shrinkage values for SF20GF10 were 0.53% and 0.85% and the values for SF10GF20 were 0.47% and 0.88% respectively. Comparison was made with the shrinkage requirements of an automotive material specification suggesting that hybrid biocomposites with optimized IM parameters meet the dimensional requirements of automotive parts.

1. Introduction

In today's competitive market, materials that can offer light-weighting while maintaining or improving function, provide environmental benefits and reduce the cost are attractive to the automotive manufacturers. Natural-fiber reinforced composites "biocomposites" is an emerging market due to such advantages that these materials can offer over conventional glass-fiber and mineral-filled plastics. Due to the fact that average vehicle uses double the amount mineral-filled and glass-reinforced plastic composite today than seven years ago, the opportunity for using biocomposites is expected to grow as replacement materials in automotive applications [1–3]. The use of biocomposites from natural fibers and polypropylene in automotive interior components is not a new concept [4–7]. However, their use in under-the-hood application is relatively new because of their lower thermal and impact performance [8,9]. Due to the new advances in polymer chemistry and natural fiber pre-treatment and processing method, the opportunity for developing biocomposites with enhanced properties for under-the-hood application is enormous.

Despite economic and environmental benefits, manufacturing of biocomposite parts cannot compromise the quality requirements of an automaker. In order to stay competitive in a present-day market, producing higher quality products at a fast rate with maximum dimensional accuracy is critical [6,7]. Injection molding (IM) process is widely used in manufacturing plastic composites including many under-the-hood parts due to faster production cycles, excellent surfaces of the products and facile molding of complicated shapes [12]. However, plastic composites such as biocomposites often experience discrepancies in the injection molded part dimensions or shape due to shrinkage and warpage defects [9]. As new biocomposites are emerging for under-the-hood application, it is important to understand the root cause of these defects and minimize these defects prior to developing parts [8,9].

From the existing literature, shrinkage defect in fiber-reinforced plastic composites is often associated with a combination of factors such as material properties, mold design and process parameters [2,5]. Unsuitable process parameter settings can cause many production problems such as product defects, long lead time and high cost [14]. Moreover, other factors such as polymer flow anomalies as a result of fiber reinforcement and differences in thermal properties between the mold and the polymer can ultimately lead into shrinkage defects in the molded part [7,11]. Since mold design

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http://dx.doi.org/10.1016/j.compositesa.2015.10.034
1359-835X/

changes are costly, complex and time consuming, first and the most effective approach to develop parts that meet the dimensional requirements is via process optimization [2,6].

Various optimization methods such as Taguchi [12,13], integrated response surface method [18], genetic algorithm [19], grey theory [20] and neural network [21] have been implemented to improve process, product and design. Kamoun et al. [14] applied sequential simplex method for on-line optimization of selected nine injection molding (IM) parameters in order to minimize rejects from 8.0% to 1.6%. Other studies reported using a combination of computer simulation and statistical approach to optimize IM process parameters [16,18,19]. Despite various methods, Taguchi method is the most common IM parameter optimization tool due to its robust and simple experimental design approach based on the conventional statistical concepts [24,25]. Most of the reported literatures on hybrid biocomposite have been focused on understanding the relationship between optimal processing conditions and mechanical properties [9,21,26]. Other studies on conventional polymers and fiber-reinforced composites have evaluated the relationship between IM processing parameters and the shrinkage and warpage defects [10,23]. Barghash and Alkaabneh [12] found that filling time, melt temperature, mold temperature and holding time have significant effect on shrinkage and warpage defects. Similarly, injection pressure, hold pressure and cooling time have shown significant influence on shrinkage and warpage defects [10,13,22]. Study on glass fiber reinforced plastic composites showed that decrease in hold time caused 30% increase in warpage while decrease in mold temperature dropped warpage by 60% [28]. The same study also suggested a direct correlation between the difference in flow and x-flow shrinkage with warpage factor [28]. Nevertheless, systemic investigations of dimensional properties of hybrid biocomposites as a function of IM processing conditions have not been addressed in the literature till date. Present work follows the study by KC et al. [29] in developing lightweight and sustainable sisal-glass fiber hybrid biocomposite with the enhanced thermal and mechanical properties. In order to evaluate and improve tolerance of injection molded hybrid biocomposite parts, the variations due to IM processing conditions have to be quantitatively assessed and optimal processing guidelines must be established [7,11].

This study reports on the optimization of injection molding (IM) parameters of two hybrid biocomposites from sisal fiber (SF) and glass fiber (GF) with an aim to minimize flow and cross-flow (x-flow) shrinkage. Two hybrid formulations; 20% SF/10% GF (SF20GF10) and 10% SF/20% GF (SF10GF20) were reinforced with 70% of polypropylene to mold rectangular plaques. Based on the literature review, six IM parameters such as injection pressure, melt temperature, mold temperature, holding pressure, cooling time and holding time were selected as main factors to influence quality characteristics (flow and x-flow shrinkage). A mixed-level Taguchi design with L18 orthogonal array was used to identify optimal settings of main control factors in order to achieve minimum shrinkage and ANOVA was used to evaluate the significant control factors. Comparison of shrinkage values was made with the currently approved automotive material specification in order to validate the optimal IM conditions.

2. Materials and methods

2.1. Materials

Polypropylene (PP) homopolymer with MFI 40 g/10 min was supplied by Braskem. Sisal fiber (SF) of fiber length 3–5 mm and density 1.1 g/cc was obtained from Hamilton Rios, Brazil whereas glass fiber (GF) with 10–11 mm length and density 2.5 g/cc was supplied from VI Fiberglass, Brazil.

2.2. Hybrid biocomposite fabrication

Two hybrid biocomposites: SF20GF10 and SF10GF20 were developed using process explained in the previous study [29]. The extrudates were immediately cooled by water and cut into pellets (~5 mm) using in-line pelletizer. The pellets were dried for 10 h at 80 °C to achieve moisture content below 0.5% prior to injection molding.

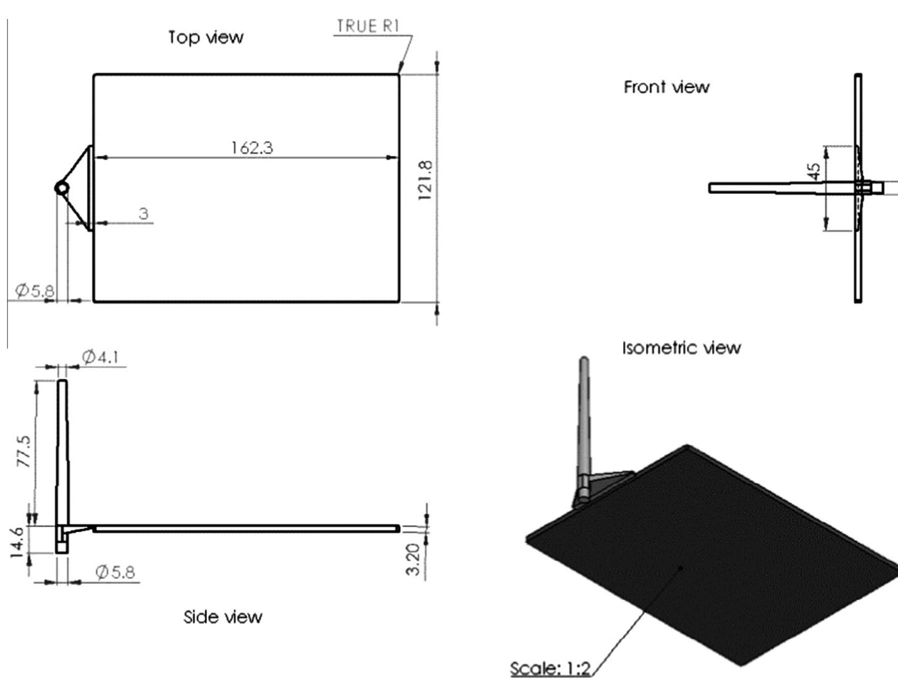

Fig. 1. Schematics of the rectangular plaque design.

2.3. Injection molding (IM) process conditions

Hybrid biocomposite pellets were injection molded (ROMI Pratica 130, Brazil) into a rectangular plaque of dimension 16.2 cm × 12.2 cm × 0.32 cm (Fig. 1). The mold cavity with an edge gate and four cooling channel diameter of 1.5 cm was used. During injection molding experiments, each process condition was allowed to stabilize temperature for 5 min and molded 5 rectangular plaques at that condition. First two samples were discarded and the last three samples were used for a shrinkage measurement. For confirmation experiment, eight rectangular plaques were molded using optimal injection molding conditions from Taguchi analysis. For comparison, additional plaques from 30% sisal fiber polypropylene composite (SF30GF0), and pure PP were molded using their optimal process conditions [29]. SF30GF0 is a representative material approved for automotive interior and exterior application [30]. All injection molded plaques were conditional at 5 °C ± 2 and 50% relative humidity (RH) for 48 h prior to analysis.

2.4. Taguchi experiment

The experiments for two hybrid biocomposites consisted of L18 orthogonal array with mixed two-three level design (Table 1). Combination of experiment with six main factors and their levels are given in Table 2. Additional IM parameters such as injection velocity, injection time, and melting velocity were kept constant to control process variables. Average S/N ratio for response table was determined using Minitab® software's 'Analyze Taguchi Design' function. The S/N ratio measures sensitivity of shrinkage due to controlled factors versus the noise factors [25]. Higher S/N ratio value suggests smaller variance around the target value and less likelihood of random effects of the noise factors [17]. Calculation of average S/N ratio for each level has been illustrated by Tang et al. [31].

2.5. Shrinkage measurement

Shrinkage measurement was performed on three rectangular molded specimens for each IM experiment according to ASTM-D955 standard. Length and width of molded rectangular plaques were measured after using Vernier caliper with an accuracy of ±0.001 mm. Measurements of length in flow direction are $L1$, $L2$, $L3$ and $L4$ while the measurements of width in x-flow direction are $W1$, $W2$, $W3$ and $W4$ as shown in Fig. 2. Shrinkage was calculated using Eqs. (1) and (2) given below.

$$\text{Shrinkage in flow direction, Ls} = [L_m - \text{Mean}(L1 \ldots L4)]/L * 100\% \quad (1)$$

$$\text{Shrinkage in x-flow direction, Ws} = [W_m - \text{Mean}(W1 \ldots W4)]/W * 100\% \quad (2)$$

where L_m & W_m are the length and width of the plaque mold respectively. Taguchi analysis was performed using Minitab software. For ANOVA analysis, signal-to-noise (S/N) ratio of smaller the better was employed and calculated using Eqs. (3) and (4).

For smaller the better S/N ratio,

$$S/N = -10\log(MSD) \quad (3)$$

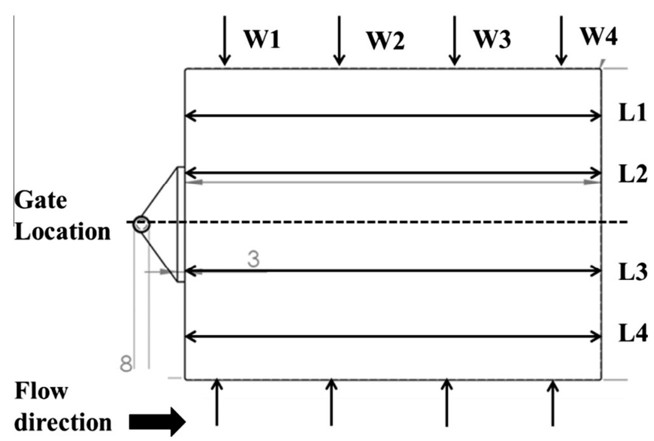

Fig. 2. Shrinkage measurement locations in a rectangular plaque.

Table 1
Injection molding factors and levels selected in the DOE.

Factors	Levels		
	1	2	3
Injection pressure (Bar)	80	90	–
Melt temperature (°C)	190	200	210
Mold temperature (°C)	40	50	60
Holding pressure (Bar)	50	60	70
Cooling time (s)	35	40	45
Hold time (s)	4	6	8

Table 2
Summary of L18 orthogonal array used for the DOE.

Experiment No.	Injection pressure	Melt temperature	Mold temperature	Holding pressure	Cooling time	Holding time
1	80	190	40	50	35	4
2	80	190	50	60	40	6
3	80	190	60	70	45	8
4	80	200	40	50	40	6
5	80	200	50	60	45	8
6	80	200	60	70	35	4
7	80	210	40	60	35	8
8	80	210	50	70	40	4
9	80	210	60	50	45	6
10	90	190	40	70	45	6
11	90	190	50	50	35	8
12	90	190	60	60	40	4
13	90	200	40	60	45	4
14	90	200	50	70	35	6
15	90	200	60	50	40	8
16	90	210	40	70	40	8
17	90	210	50	50	45	4
18	90	210	60	60	35	6

$$MSD = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (4)$$

where *MSD* is the mean square deviation, y is the shrinkage value and n is the number of tests in a trial.

3. Results and discussion

3.1. Shrinkage analysis

Shrinkage is defined as the difference between the size of the mold cavity and the size of the finished part divided by the size of

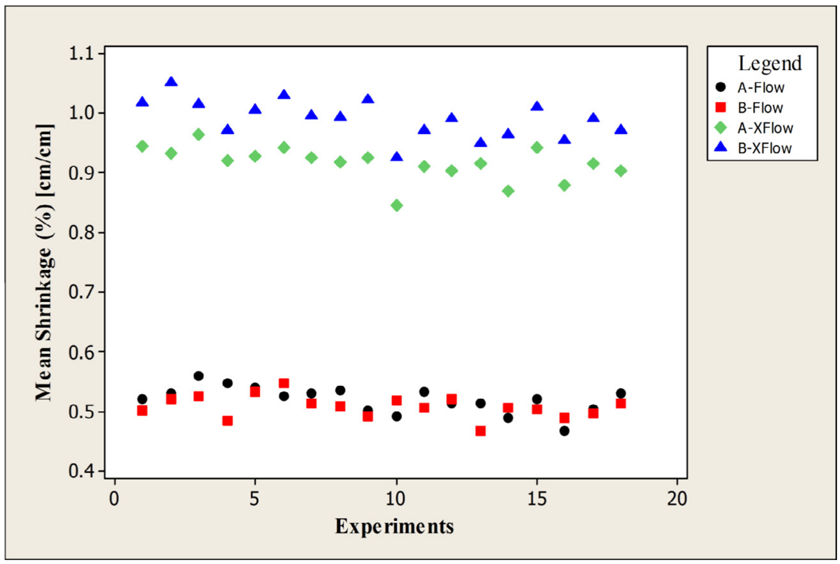

Fig. 3. Mean shrinkage in flow and cross (x)-flow direction of hybrid biocomposites; SF20GF10 (A) and SF10GF20 (B). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

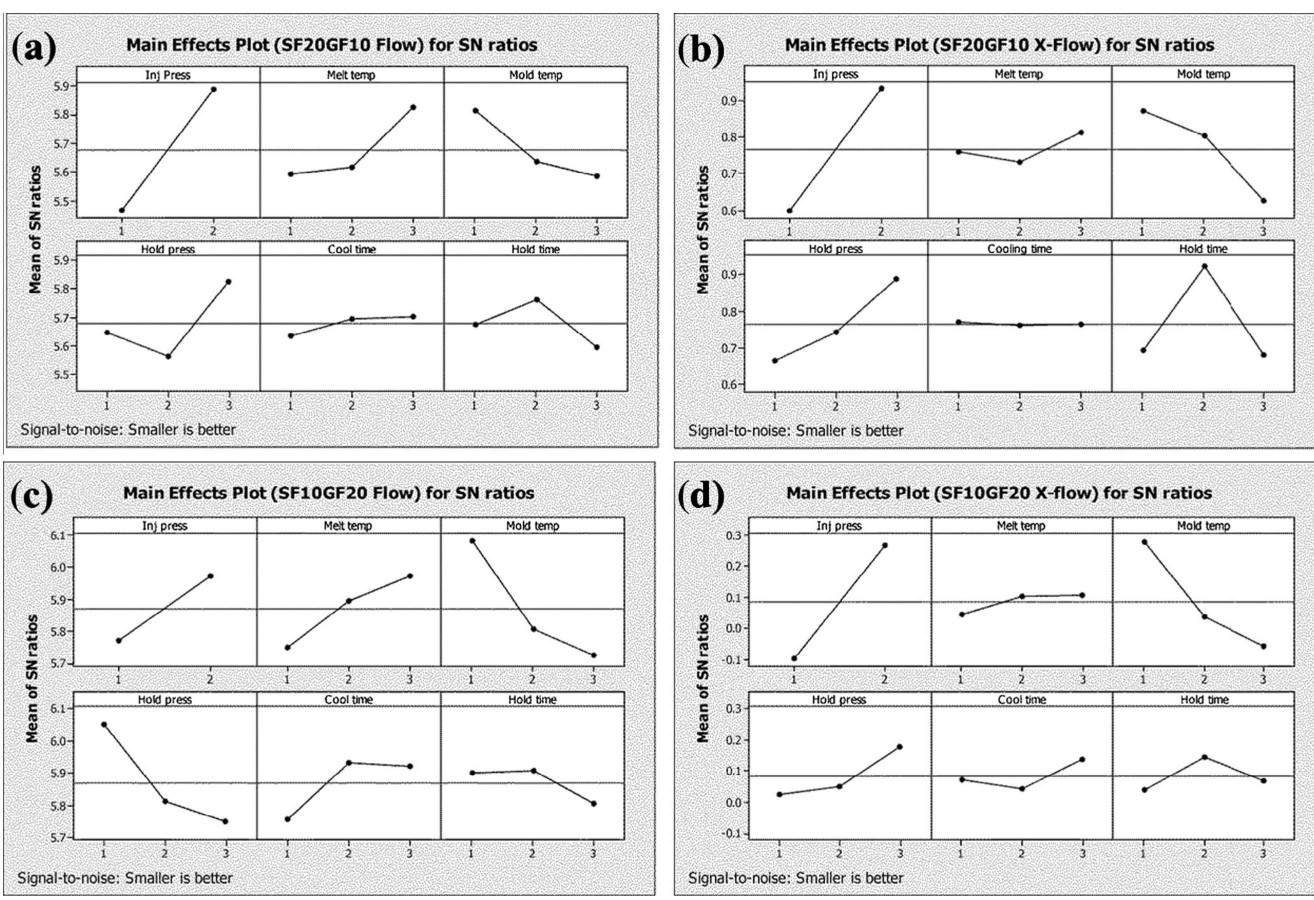

Fig. 4. Main effects plot of S/N ratios for flow (a and c) and x-flow shrinkage (b and d) of SF20GF10 and SF10GF20.

Table 3
Average response table for means of SF20GF10 in flow direction.

Level	Injection pressure	Melt temperature	Mold temperature	Hold pressure	Cool time	Hold time
1	0.5330	0.5257	0.5125	0.5222	0.5226	0.5201
2	0.5079	0.5238	0.5229	0.5270	0.5197	0.5156
3	–	0.5119	0.5259	0.5122	0.5190	0.5257
Delta	0.0251	0.0138	0.0134	0.0148	0.0036	0.0101
Rank	1	3	4	2	6	5

Table 4
Response (rank) table for mean flow and x-flow shrinkage.

Factors	Shrinkage (Flow)		Shrinkage (X-flow)	
	SF20GF10	SF10GF20	SF20GF10	SF10GF20
Injection pressure (Bar)	1	4	1	1
Melt temperature (°C)	3	3	5	6
Mold temperature (°C)	4	1	2	2
Holding pressure (Bar)	2	2	4	3
Cooling time (s)	6	5	6	5
Hold time (s)	5	6	3	4

a mold [24]. Relative shrinkage of the hybrid biocomposites in flow and x-flow direction were calculated and summarized in Fig. 3 below. Relatively higher shrinkage was found in the x-flow direction compared to flow direction for both hybrid biocomposites. This has been associated with the flow-induced fiber and polymer molecule orientation [11]. However, both hybrid biocomposites showed similar shrinkage in flow and x-flow direction.

3.1.1. Optimal process variables and their levels

In Fig. 4, S/N ratios are plotted for each factor and their levels. Using experimental data, optimal mean shrinkage and S/N values were predicted using 'Predict Taguchi Results" function in Minitab® software. The predicted optimal conditions for SF20GF10 and SF10GF20 were similar except for the holding pressure. Optimal factor levels for flow shrinkage of both hybrid biocomposites were injection pressure 90 bar, melt temperature 210 °C, mold temperature 40 °C, cooling time 40 s and hold time 6 s (Fig. 4a and c). However, optimal holding pressure was 70 bar and 50 bar for SF20GF10 and SF10GF20 respectively. In comparison with the flow shrinkage, response of each factor on x-flow shrinkage was similar (Fig. 4b and d). Moreover, S/N ratio for x-flow shrinkage was smaller than the ratio for flow shrinkage possibly due to lower influence of IM parameter on x-flow shrinkage.

From the literature, higher holding pressure, melt temperature and mold temperature generally resulted in lower shrinkage [15]. Similarly longer cooling time and holding time have also been found to lower shrinkage [32]. Evaluation of the optimal levels used in this study suggests that minimum shrinkage was achieved at higher level of injection pressure and melt temperature and medium levels of cooling time and holding time. It is difficult to correlate these findings with the literature as the definition of levels for each IM factor, material property and mold geometry are different from the current study.

3.1.2. Quality characteristics

Significance of each factor on the quality characteristics (flow and x-flow shrinkage) was evaluated based on maximum and minimum response values of each factor at different levels. For illustration, response table result from the Minitab© software is shown below in Table 3 where 'Delta' is calculated as

$$\text{Delta} = \text{Highest value}\ [\text{Factor X}] - \text{Lowest Value}\ [\text{Factor X}] \quad (5)$$

Ranks of 1 and 6 were given for each factor based on maximum and minimum delta values and the results are summarized in Table 4. Flow shrinkage of both hybrid biocomposites were least affected by the cooling and the holding time. In contrast, the most significant factor for flow shrinkage was injection pressure for SF20GF10 and mold temperature for SF10GF20. Furthermore, the second most influencing factor for both hybrid biocomposite was holding pressure. For x-flow shrinkage, melt temperature and cooling time had the least influence for both hybrid biocomposites. In contrast, the most significant factor for x-flow shrinkage was injection pressure followed by mold temperature. Despite varied response between two hybrid biocomposites and also between flow and x-flow shrinkage, the information is useful in selecting important parameter for future full-factorial studies as recommended by Barghash and Alkaabneh [12].

3.2. ANOVA analysis

ANOVA analysis is used to determine which parameter has a significant impact on the quality characteristics [27]. ANOVA was performed for mean flow and x-flow shrinkage values using General Linear Model (GLM). The summary of degree of freedom (DOF), F-ratio (F) and percent contribution for each factor (P) was calculated and is summarized in Table 5 for SF20GF10 and Table 6 for SF10GF20. Higher 'F' value suggests that the effect of a factor is larger compared to error variance suggesting important parameter for influencing the quality characteristics. Based on F distribution table at 95% confidence interval, $F_{05}\,(f1, f2)$ value for injection pressure is 4.41 and rest of the factors is 3.55 [33].

Table 5
ANOVA analysis of shrinkage in flow and x-flow direction for SF20GF10.

Factors	Shrinkage (Flow)				Shrinkage (X-flow)		
	DOF	Sum of squares (SS)	F	P	Sum of squares (SS)	F	P
Injection pressure	1	0.00284	4.52	31.87	0.00546	16.39	39.43
Melt temperature	2	0.00067	0.53	7.52	0.00024	0.36	1.743
Mold temperature	2	0.00060	0.47	6.65	0.00211	3.17	15.25
Hold pressure	2	0.00069	0.55	7.72	0.00164	2.47	11.91
Cool time	2	0.00004	0.03	0.49	0	0	0.021
Hold time	2	0.00031	0.24	3.44	0.00238	3.57	17.20
Error	6	0.00376		42.30	0.00199		14.44
Sum	17	0.00890			0.01385		

Table 6
ANOVA analysis of shrinkage in flow and x-flow direction for SF10GF20.

Factors	Shrinkage (Flow)				Shrinkage (X-flow)		
	DOF	Sum of squares (SS)	*F*	*P*	Sum of squares (SS)	*F*	*P*
Injection pressure	1	0.000621	2.28	10.72	0.007677	15.46	44.88
Melt temperature	2	0.000498	0.92	8.61	0.000191	0.19	1.12
Mold temperature	2	0.00143	2.63	24.71	0.00455	4.58	26.60
Hold pressure	2	0.001073	1.97	18.54	0.000961	0.97	5.62
Cool time	2	0.0004	0.73	6.91	0.000336	0.34	1.97
Hold time	2	0.000134	0.25	2.31	0.000411	0.41	2.40
Error	6	0.001633		28.21	0.00298		17.42
Sum	17	0.005788		100	0.017106		100

Table 7
Comparison between predicted and experimental flow and x-flow shrinkage in hybrid biocomposites.

Materials	Flow shrinkage (%)		X-flow shrinkage (%)	
	Predicted (Taguchi)	Experiment (±SD)	Predicted (Taguchi)	Experiment (±SD)
SF20GF10	0.4769	0.5346 (±0.015)	0.8530	0.8742 (±0.02)
SF10GF20	0.4680	0.4718 (±0.021)	0.9233	0.8864 (±0.005)

Percentage contribution (P) from each factor was calculated as follows.

$$P = SS_{factor}/\text{Total SS} \times 100\% \tag{6}$$

where SS_{factor} = sum of squares

Based on the analysis of '*F*' value, only injection pressure showed significant influence on flow shrinkage ($P = 31.9\%$) of SF20GF10. For x-flow shrinkage, both injection pressure ($P = 39.4\%$) and hold time ($P = 17.2\%$) had significant effect. In contrast, no factors had significant effect on flow shrinkage of SF10GF20; however, x-flow shrinkage was significantly affected by injection pressure ($P = 44.9\%$) and mold temperature ($P = 26.6\%$). The factors that were not significant in the experiment may still have an individual effect on shrinkage but the overall effect could be minimal. This is the case for mold temperature that produced lower significance ($F_{05} < 3.55$) despite contributing to flow shrinkage by 24.7% (Table 6). Among two hybrid biocomposites, the effect of mold temperature on shrinkage (both flow and x-flow) of SF10GF20 was higher. It is possible that relatively higher thermal conductivity of SF10GF20 due to 20% glass fiber may have increased the sensitivity of SF10GF20 towards mold temperature. With cooling time as the least significant factor for shrinkage, it is likely that flow-induced stresses during filling and packing stage of IM process had a dominant role in the formation of residual stress leading to shrinkage defects [15]. In addition, Nasir et al [17] found that melt temperature was also a significant contributing factor for shrinkage and warpage defects on both single

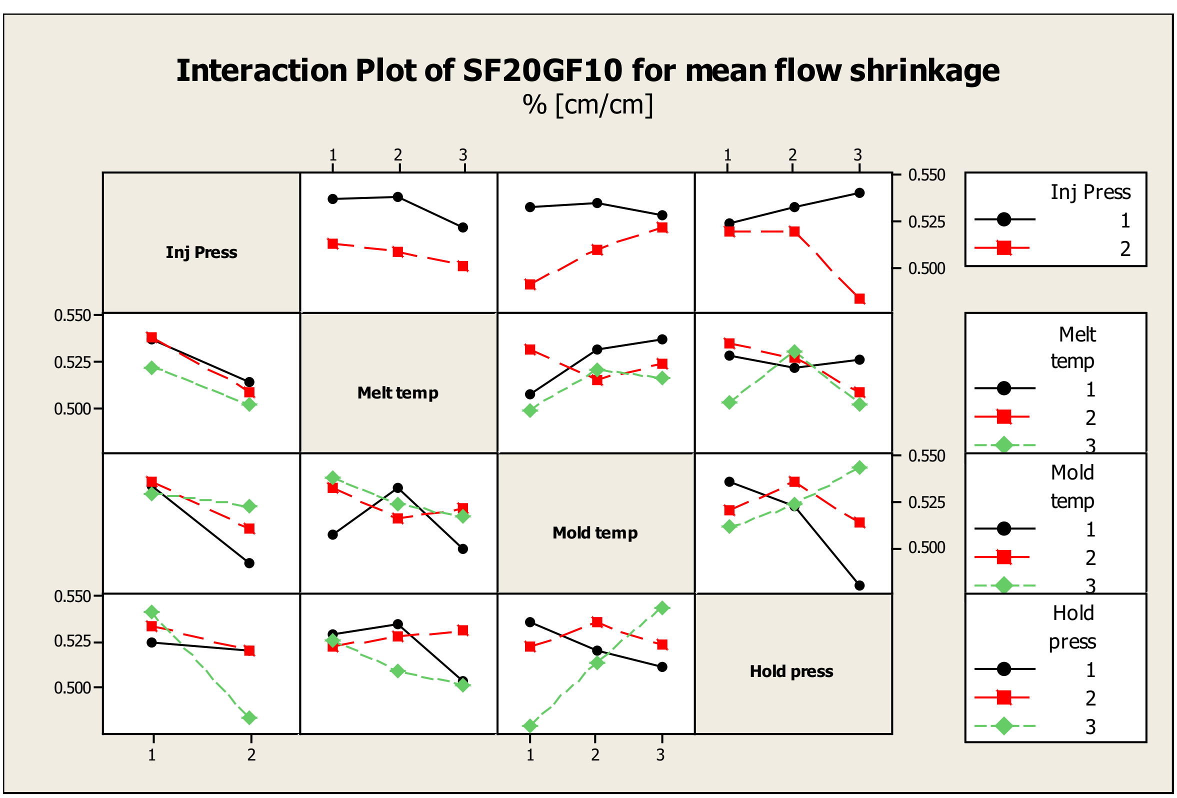

Fig. 5. Interaction plot of SF20GF10 for mean flow shrinkage using Minitab® software. Interaction between injection parameters; injection pressure, melt temperature, mold temperature and hold pressure at the selected levels (Table 1) is shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

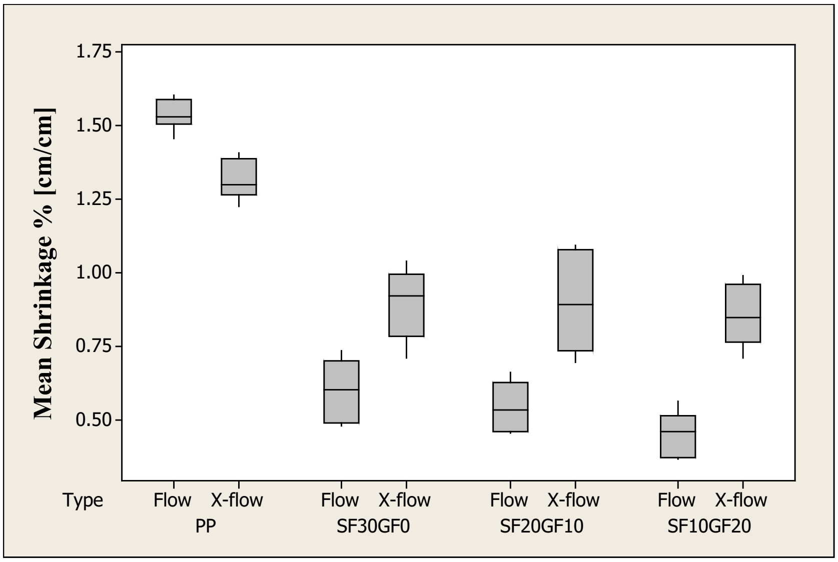

Fig. 6. Boxplot of PP, SF30GF0 and two hybrid biocomposites (SF20GF10 and SF10GF20) mean shrinkage with optimized injection molding conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(P = 66.5%) and multigate designs (P = 22.2%) on tensile specimens. Tang et al. [31] illustrated that melt temperature was the most effective factor contributing to warpage followed by holding time and holding pressure.

3.3. Confirmation test

A confirmation test is performed to validate the results of Taguchi optimization and provide evidence that interaction effects between factors are low [11]. In practice, it is very hard to state with confidence how close the experiment number must come to the predicted values for the agreement to be considered good. Hence, it can only be applied for the present set of parameters. Table 7 summarizes flow and x-flow shrinkage data from Taguchi prediction and experimental verification test. All experimental values are within a 5% difference from predicted results except for flow shrinkage of SF20GF10 (10.8%). Such a deviation from experimental value can be attributed to interaction between factors that were less significant to the response during ANOVA analysis. From Fig. 5, some interaction was found between all injection molding parameters of SF20GF10 and the selected factors (Table 1). Slightly higher interaction was also observed between holding pressure, mold temperature and injection pressure. Similar differences in predicted and experimental values were found by Prashantha et al. [11]. Most importantly, in this study both hybrid biocomposite exhibited shrinkage in flow and x-flow below the material maximum shrinkage requirement (1.2%) in automotive material used for under-the-hood parts such as battery tray and fan shroud [34].

3.4. Shrinkage comparison

In order to validate the optimal IM condition, flow and x-flow shrinkage of both hybrid biocomposite were compared with SF30GF0 that is approved for interior and exterior application and pure PP as a reference material [30]. Comparison of flow and x-flow shrinkage is shown in Fig. 6. It was found that addition of 30% fiber in PP reduced both flow and x-flow shrinkage significantly due to the restriction of polymer relaxation from rigid glass and sisal fiber. Overall result suggests that flow and x-flow shrinkage properties of both hybrid biocomposites are similar to SF30GF0. It can be implied that hybridization of sisal and glass fiber does not significantly influence the flow and x-flow shrinkage characteristics of SF30GF0 and most likely meet the requirements of both interior and exterior automotive application. Moreover, small difference in flow and x-flow shrinkage (differential shrinkage) of SF30GF0 and two hybrid biocomposites suggests lower risk of warpage defects in fiber-reinforced plastic [28]. This information is particularly important when designing a tool or developing an optimal process for hybrid biocomposites. It is due to the fact that common ASTM and ISO standards method for measuring shrinkage ignore the anisotropic shrinkage characteristics that may lead to warpage defects [28].

In comparison to PP, flow shrinkage reduced in SF30GF0 and two hybrid biocomposites with the fiber reinforcement while x-flow shrinkage relatively remained constant. It is the result of increase in rigidity of a material due to an addition of fibers or fillers which makes it less sensitive to process variations during injection molding [11].

4. Conclusions

The current investigation optimizes and evaluates the effect of injection molding parameters on flow and x-flow shrinkage of sisal-glass hybrid biocomposies. For both hybrid biocomposites (SF20GF10 and SF10GF20), optimal injection molding settings for minimizing flow shrinkage are injection pressure 90 bar, melt temperature 210 °C, mold temperature 40 °C, cooling time 40 s and hold time 6 s while optimal holding pressure was 70 bar for SF20GF10 and 50 bar for SF10GF20. Based on ANOVA analysis, injection pressure had a significant influence on both flow shrinkage and x-flow shrinkage of SF20GF10. For SF10GF20, no factors showed significant impact on flow shrinkage; however injection pressure and mold temperature had a significant impact on x-flow shrinkage. Other factors did not have a significant impact on shrinkage measurement due to larger error variance and was attributed to interaction effect between the selected factors. This information can be critical for selecting important factors in full-factorial experiment. Confirmation test resulted in 11% variation between predicted and experimental flow shrinkage values of SF20GF10 and 4% variation in predicted and experimental x-flow values of SF10GF20. Upon evaluation of optimized shrinkage data for both hybrid biocomposites, the values were similar to SF30GF0 and below the specified shrinkage limit of 1.2% for under-the-hood parts such as battery tray and fan shroud.

In summary, Taguchi method provides an effective solution to optimize injection molding parameters and evaluate their influence on shrinkage. In future, shrinkage information from this study can be used to design a tool for developing hybrid biocomposite automotive parts.

Acknowledgements

Authors would like to thank CAPES-DFAIT program and Automotive Partnership Canada (APCJ 433821-12) for funding this research. We are also thankful to all the technical staffs at DEMa, UFSCAr (Brazil) and Mrs. Anuja Siwakoti for proofreading this manuscript.

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