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Article

Evaluation of plastic injection molding for PA6/ABS/$CaCO_3$ nanocomposites using Taguchi method and Moldflow simulation approach

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ABSTRACT

Nowadays, nanocomposites are widely used in the industry. Polymer nanocomposites are widely used in the automotive industry because they have very favorable properties. These properties, including mechanical, electrical, and thermal characteristics, change depending on the combination of materials used in composite synthesis. In this paper, the injection molding of an automobile part called a control arm protector is investigated. Since warpage and shrinkage are general and important challenges in injection molded parts, Taguchi test design and Autodesk Moldflow® simulation approach are used to find the best injection condition for the mentioned part. To perform this, PA6/ABS polymer composite combined with nano $CaCO_3$ is used. Three main injection molding process parameters, including melt temperature, mold temperature, and injection pressure, as well as nano $CaCO_3$ amount, are evaluated. Moreover, analysis of the gate location is investigated. In the following, an analysis of variance is conducted to identify the significant parameters. Regression correlations were also established. Finally, optimization of the process is carried out by the desirability method.

1. Introduction

Today, injection molding is one of the most widely used manufacturing processes [1]. Besides, that is possible to use new polymer alloys and composites in order to improve plastic products. Injection-molded plastics are widely used for mass production, especially in the automotive industry. However, it is a challenge to produce parts that are free of defects, such as warpages, jetting, voids, etc. [2]. During the injection molding process, some defects occur in plastics, which affect the performance and appearance of the product. Identifying problems produced through the injection process depends on factors such as mold design, polymer specifications, and process conditions [3]. Polyamide (PA) is a thermoplastic and semicrystalline polymer that is in different types. PA6 is the most popular grade of polyamide (sometimes seen as nylon 6). The strength, stiffness, and toughness properties of Polyamide 6 have made it known as an engineering plastic [4]. PA6 has high modulus, strength, impact properties, and wear resistance with a low friction coefficient [5]. Due to their high crystallinity, most polyamides show significant properties. For example, PA6 and PA66 - two important products of the polyamide family - when combined with other polymers, induce properties including solubility resistance (e.g. gasoline, oil, paint solvents, etc.), high heat resistance and excellent melt flow properties [6]. On the other hand, the main purpose of combining PA6 with other polymers is to reduce the sensitivity to water absorption in polyamide and improve its dimensional stability. Among styrene resins, Acrylonitrile Butadiene Styrene (ABS) polymer is considered an engineering thermoplastic polymer. Because it has properties such as high impact strength, solubility resistance, and moderate heat resistance. Besides, due to the relatively low price of ABS compared to other plastics, this plastic can be used as an intermediate between cheap and expensive engineering thermoplastics. Moreover, ABS has disadvantages such as low bending and tensile strength and dimensional stability at high temperatures [7]. The purpose of combining PA6 and ABS is to balance toughness and stiffness. In the meantime, due to the commerciality of PA6/ABS and the interesting properties of this polymer alloy, researchers have conducted several studies on the properties of this material and compatibilizers between PA6 and ABS. In addition, in order to increase the mechanical properties of this mixture for use in industrial applications, glass fibers have been used with different percentages [8], and the conducted research shows the improvement of the elastic properties by using glass fibers [9]. Of course, the addition of glass fibers also reduces the PA6 moisture absorption and fluidity [10, 11], which diminishes the moldability of thin sections of the parts form PA6. Additionally, the abrasive properties of glass fibers significantly increase the wear of molding equipment, including cylinders, screws, and molds. In industry, in addition to glass fibers, micro-mineral particles are also used to strengthen polymers one of these materials is calcium carbonate particles [12]. These particles are basically used in micron-sized form in order to strengthen various polymer compounds. Nowadays, by developing nanotechnology, using nanomaterials was proposed aimed at improving the mechanical and physical properties of polymers. Nanocomposite refers to materials that have at least one component in nanometer dimension [13]. Shelesh-nezhad et al. [14] investigated crystallization, shrinkage, and mechanical specifications of Polypropylene (PP)/nano $CaCO_3$ composites and declared by low nanoparticle incorporation, shrinkage amount is decreased. Wang et al. [15, 16] studied on ABS/$CaCO_3$ and Low-Density Polyethylene (LDPE)/$CaCO_3$ composites. Rheological specifications of ABS/ nano $CaCO_3$ were also examined by Tang et al. [17]. Moreover, Premphet et al. [18] have conducted research on ternary PP/elastomer/$CaCO_3$ composite. Recently, since cost is an important factor in industry and manufacturing processes, Computer Aided Engineering (CAE) has been developed, and new approaches have been suggested in order to predict the possible defects in the final product before the experimental producing step. In this regard, various software has been introduced in order to examine and optimize the injection molding process by simulating different aspects of the process, including shrinkage, warpage, melt flow, cooling, clamping force, etc. Autodesk Moldflow® is one of the famous software that is widely used in the industry and lets the operator troubleshoot problems with injection molding and compression molding. Nonetheless, different studies have been conducted in order to evaluate the injection process using Moldflow® software. Martowibowo et al. [19], by using Moldflow® and a genetic algorithm, optimized the injection molding process. Vishnuvarthanan et al. [3] conducted an optimization on injection molding in order to reduce process cycle time. Li et al. [20], based on the Taguchi Design Of Experiment (DOE) simulated and optimized the injection molding process. Oliaei et al. [21] optimized warpage and shrinkage for producing a plastic spoon part using Moldflow® and Taguchi techniques. Other researchers have also conducted optimization on injection molding [22-26]. Especially automotive industry is an interesting zone for the simulation process. Ganeshram et al. [27] designed and analyzed piston cooling nozzles in automobiles using Moldflow® software. In this paper, the injection molding of a small specimen in the suspension system of the car called the control arm protector was examined. This part is exposed to a lot of vibrations, and as a result, it has a very high failure rate. Hence, dimensional tolerance should be considered as an important factor. Shrinkage and warpage are the significant parameters that influence the dimensional precision of the part. In this regard, Moldflow® software and the Taguchi method have been used in order to optimize the injection process. In this investigation, in addition to injection process parameters, nano $CaCO_3$ percentage will be evaluated.

2. Materials & Methods

A small specimen in the suspension system of a car called the control arm protector was selected to perform this investigation. This part is designed in Solidworks software. The part is circular and mostly plays the role of a damper in the suspension system. The part dimensions are shown in Figure 1.

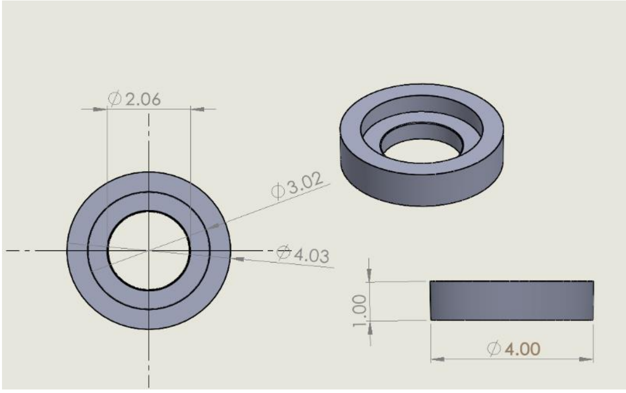

Figure 1. Part dimensions

Nevertheless, three types of materials based on PA6, ABS and nano $CaCO_3$ are used to analyze in Moldflow® software to check the effects of different parameters on shrinkage and warping. Properties of the used composites are shown in Table 1 in order to be placed in Moldflow® software. The values of Table 1 have been placed instead of the mechanical properties of the materials in Moldflow®. Besides the location of the gate has also been inspected. The location of the gate is one of the factors that affect warping. The flow resistance indicator is shown in Figure 2, and gating suitability is shown in Figure 3. From Figure 2, it can be seen that the highest flow resistance will be marked red, and the lowest resistance is in dark blue. In Figure 3, the suggested mode by Moldflow® is used to select the gate location. The process diagram and investigation sequences are depicted schematically in Figure 4.

Table 1. Properties of the used nanocomposites

	ABS/PA6	ABS/PA6/%2C	ABS/PA6/%5C
Tensile strength (MPa)	30.4	32	40
Tensile modulus (GPa)	2.568	1.874	2.605
Elongation at break (%)	107.1	216.5	286
Izod impact strength (KJ/m²)	10.31	27.5	15.94

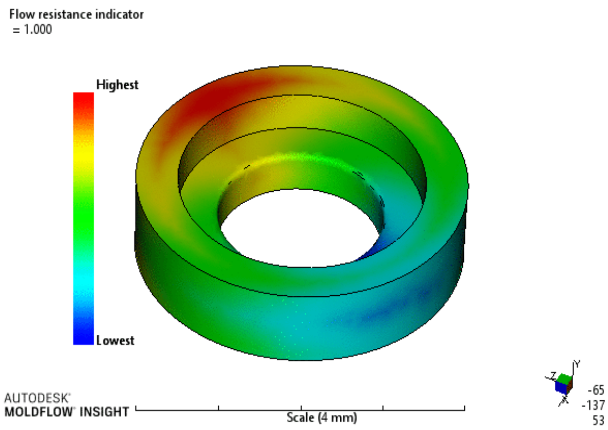

Figure 2. Flow resistance indicator

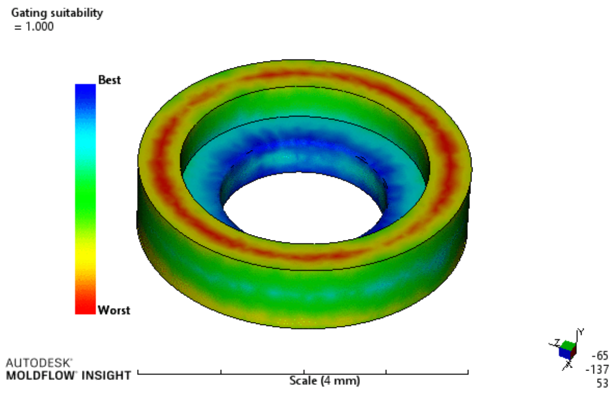

Figure 3. Gating suitability

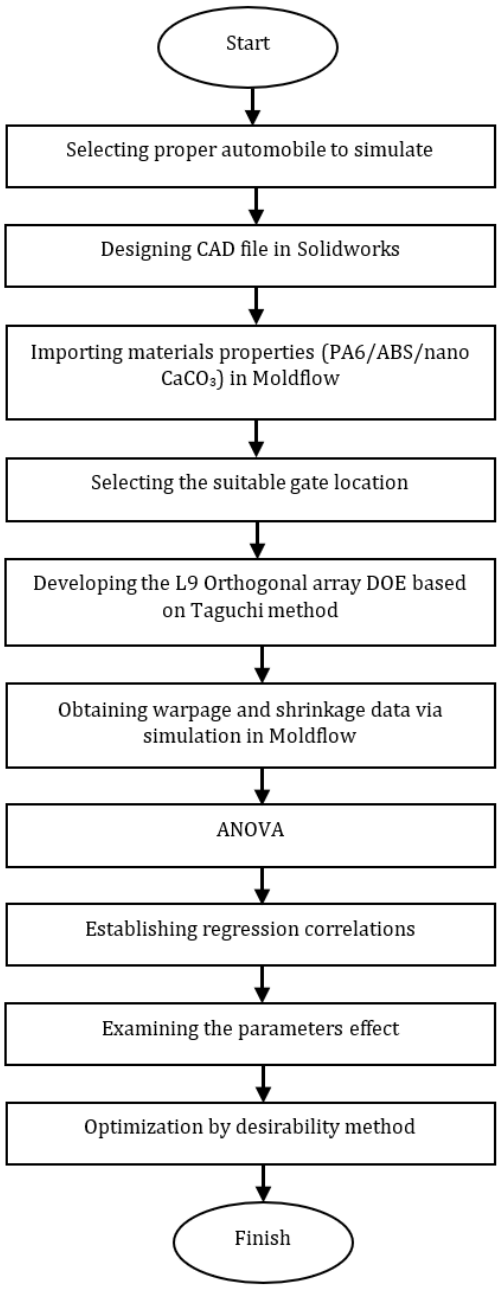

Figure 4. Investigation sequences

3. Results and Discussion

3.1 Moldflow® simulation

In this work, four input parameters have been considered: melt temperature, mold temperature, injection pressure, and nano percentage. The tests have been performed at three levels. The input parameters are specified in Table 2. DOE is a set of actions performed by modeling and optimizing reaction variables through statistical methods in order to increase product efficiency without increasing its price [28]. In traditional experimental design methods, only one factor was considered as a variable and other factors were placed at a constant level, which is called one variable at a time. In this method, the mutual effects between the variables are not studied, and the full effects of the factors in the process cannot be shown. Also, to conduct the research, a large number of experiments were required, which led to an increase in time and cost, as well as an increase in the consumption of reagents and materials [25]. Taguchi's method shows how engineers can produce higher-quality products at a lower cost by designing experiments. The focus of this method is on removing the factors that decrease the quality of the product. This method is a strategy to improve the quality of the process and reach a strengthened product by using the method of designing experiments and was first introduced by a Japanese engineer named Genichi Taguchi in 1986. The design is organized based on the minimum resources, time, and number of possible tests. The Taguchi method has made it possible to provide this vital information with a reduced number of trials and experiments. Taguchi developed a family of fractional factorial schemes, which are used in various applications [29]. In this article, this method is used to conduct the experiments. The provided DOE is shown in Table 3.

Table 2. Input parameters

Parameters	Symbol	Levels		
		1	2	3
Melt temperature (°C)	A	220	240	260
Mold temperature (°C)	B	50	60	70
Injection pressure (MPa)	C	50	60	70
Nano $CaCO_3$ (%)	D	0	2	5

Table 3. L9 orthogonal array (3^4)

Run No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Moldflow Insight and Synergy® have been used to simulate the injection process. The designed part after meshing has 11640 elements of dual domain type (Figure 5). After meshing, the simulation tests have been conducted (Based on Table 3). The simulation results for warpage and shrinkage are depicted in Table 4 (Appendix I). Based on Table 4 (Appendix I), that is shown maximum warpage occurs at the part peripheral, which is because of having a higher temperature compared to the inner areas of the part. The results obtained from Taguchi and Moldflow® analysis for maximum volumetric shrinkage and warpage values are shown in Table 5.

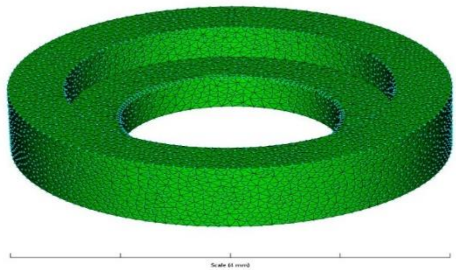

Figure 5. The meshed part

Table 5. Warpage and shrinkage results

Run No.	Warpage (mm)	Volumetric shrinkage %
1	0.0389	7.619
2	0.0397	7.755
3	0.0401	7.909
4	0.0385	8.747
5	0.0409	8.233
6	0.0388	7.750
7	0.0389	8.110
8	0.0391	8.323
9	0.0364	9.252

3.2 Statistical analysis

Moreover, Analysis of Variance (ANOVA) between the input data and the results was carried out using Minitab software (Tables 6-7). The P-value in Tables 6-7 shows the parameter significancy. Researchers consider a maximum significance level of 5% for data analysis, and a P value of less than 0.05 is significant [30]. Regression is a statistical method and is used in economics, programming, and other activities. The purpose of regression is to identify the strength and properties of a dependent variable compared to other variables (known as independent variables) [31]. Based on the results in Table 6, by performing multivariable linear regression statistical operations between the input and output data, a statistical relationship between the warpage criterion and the parameters considered in this research was presented. ANOVA is a statistical technique using the sum of squares to quantitatively examine the deviation of the average influence of each control parameter from the average influence of the entire test [32]. ANOVA for warpage results is summarized in Table 6. ANOVA results include the degree of freedom (DOF), Contribution, Sum of Squares (SS), Mean of Squares (MS), F-Value, and P-Value. The P-value and Contribution are important parameters to interpret the ANOVA table. When the P-value is low and the contribution is high, the parameter will be significant. According to Table 6, melt temperature and nano $CaCO_3$ percentage interaction have the most influence on warpage defect with 64.94% contribution. Injection pressure and mold temperature are in the next order with 9.89% and 8.43% contribution, respectively. Besides, the polynomial regression equation is correlated as Eq (1). The R^2 value for the established regression model was 96.75%, which indicates high predicting accuracy. In the following, ANOVA for shrinkage results is shown in Table 7. That indicates melt temperature has the most influence on shrinkage with a 42.7% contribution, which is in agreement with Oliaei et al. [21] research outcomes. They found melt temperature has the most influence on the shrinkage value of PLA-TPU polymer. Besides, D*D is in the next order with a 20.17% contribution, which indicates the importance of adding nano $CaCO_3$ in PA6/ABS composite. Melt temperature and nano $CaCO_3$ interaction is also significant (16.85%), similar to ANOVA of warpage. Mold temperature and nano $CaCO_3$ interaction are in the fourth order (13.61%). In addition, based on the results in Table 7, a regression relationship between the shrinkage criterion and the input parameters was constructed (Eq 2). The R^2 value is 97.08%, which specifies the high predicting power of the constructed correlation.

Table 6. Analysis of variance for warpage

Source	DF	Contribution	SS	MS	F-Value	P-Value
A	1	5.28%	0.000002	0.000002	5.52	0.256
B	1	8.43%	0.000001	0.000001	3.84	0.300
C	1	9.89%	0.000005	0.000005	14.67	0.163
D	1	4.96%	0.000006	0.000006	17.49	0.149
D*D	1	1.85%	0.000000	0.000000	0.57	0.588
A*D	1	64.94%	0.000005	0.000005	13.12	0.171
B*D	1	1.40%	0.000000	0.000000	0.43	0.630
Error	1	3.25%	0.000000	0.000000		
Total	8	100.00%				

$$\text{Warpage} = 01844 - 0.000092\,A + 0.000129\,B + 0.000172\,C - 0.01228\,D - 0.000054\,D{*}D + 0.000049\,A{*}D + 0.000011\,B{*}D \quad (1)$$

$R^2 = 96.75\%$

Using the "Ranking" statistical tool in Table 8, that is obtained Melt temperature is the most influential parameter on warpage and shrinkage, followed by Nanoparticle%, Mold temperature, and injection pressure. "Delta" means the difference between the lowest and highest average response values for each parameter. The ranking is based on the Delta value.

Table 7. Analysis of variance for shrinkage

Source	DF	Contribution	SS	MS	F-Value	P-Value
A	1	42.70%	0.15689	0.156890	2.39	0.366
B	1	1.40%	0.06886	0.068859	1.05	0.492
C	1	2.32%	0.00400	0.003998	0.06	0.846
D	1	0.03%	0.17100	0.171004	2.60	0.353
D*D	1	20.17%	0.45411	0.454105	6.92	0.231
A*D	1	16.85%	0.07757	0.077573	1.18	0.474
B*D	1	13.61%	0.30651	0.306508	4.67	0.276
Error	1	2.92%	0.06567	0.065668		
Total	8	100.00%				

$$\text{Shrinkage} = 80 + 0.0256\,A + 0.0284\,B - 0.0047\,C + 2.00\,D + 0.0799\,D{*}D - 0.00621\,A{*}D - 0.01526\,B{*}D \quad (2)$$

$R^2 = 97.08\%$

Table 8. Response data table for Means (Smaller is better)

Level	A	B	C	D
1	2.179	2.215	2.221	2.415
2	2.385	2.348	2.394	2.215
3	2.395	2.396	2.343	2.329
Delta	0.216	0.182	0.173	0.200
Rank	1	3	4	2

The main effects diagrams show the effects of each parameter on the results that plot the means for each value of a categorical variable [33]. The results obtained for warpage parameter are shown in Figure 6. Accordingly, it can be concluded by increasing melt temperature, warpage has been decreased. Melt temperature increment causes melt flow improvement. On the other hand, as injection time increases, injection rate decreases. Hence, the part surface stress and also residual stress reduces. Finally, the warp distortion of the part will be reduced. Besides, appropriate mold temperature decrement reduces crystallinity degree of the produced part and consequently reduces the warpage value. This fact was also reported by Li et al. [20]. Furthermore, as shown in Figure 6, injection pressure increment from 50 MPa to 70 MPa causes warpage increment and part distortion after rejection. Furthermore, $CaCO_3$ nanoparticle increment causes larger warpage. Incorporation of $CaCO_3$ nanoparticle raises the nucleation ability of PA6/ABS crystals and therefore results in higher crystallization [34] and larger warpage value. However, that was obtained through ANOVA results in Table 6, nanoparticle amount has very low influence on warpage value which can be neglected. The results for volumetric shrinkage are shown in Figure 7. According to Figure 7, that is indicated by increasing melt temperature, shrinkage value is increased which is due to larger temperature difference between the part and the environment temperature. This larger difference makes more time for the part to be stable which larger shrinkage will be occurred. Based on Figure 7, increasing mold temperature has the same effect on shrinkage value which is also due to higher part temperature after ejection.

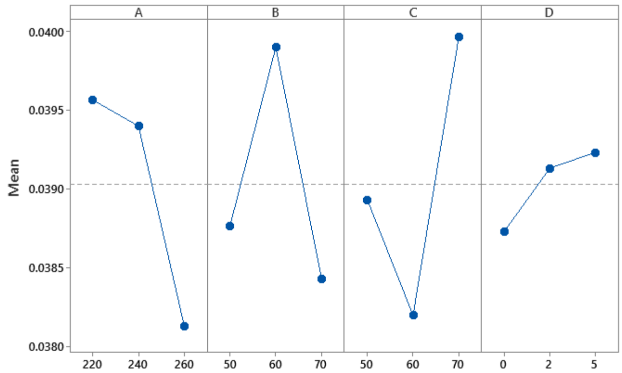

Figure 6. Main effects plot for warpage

However, Figure 7 that is indicated melt temperature is more significant compared to mold temperature. Moreover, increasing the injection pressure increases shrinkage totally. Higher injection pressure (80 MPa) compared to 50 MPa produces a more compact part. Therefore, the part shrinkage will be prevented. In addition, adding 2% nano $CaCO_3$ induces lower shrinkage. Researchers stated that adding $CaCO_3$ nanoparticles causes a higher Melt Flow Index (MFI) [14], which means more ease of melt flow. This fact induces higher moldability of PA6/ABS/2% $CaCO_3$ and lower shrinkage after ejection. In the following, by adding more nanoparticles (5%), the shrinkage value is increased. This fact is due to more crystallization in the polymer matrice in the presence of 5% $CaCO_3$ nanoparticles. Lin et al. [35] stated that adding a higher value of $CaCO_3$ nanoparticles has a nucleating effect on polypropylene polymer. On the other hand, larger nucleating leads to larger shrinkage compared to the amorphous structure.

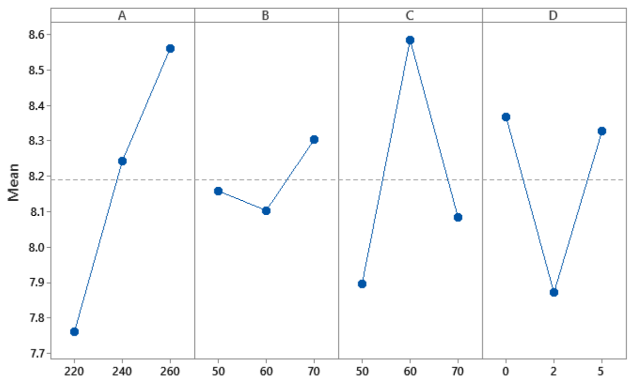

Figure 7. Main effects plot for volumetric shrinkage

3.3 Optimization

In the present paper, the desirability technique is utilized to acquire the optimum condition, which is regarding minimization of maximum volumetric shrinkage and warpage. Desirability correlations with the minimization approach are obtained through the mean of Eq (3) and Eq (4) [36]:

$$d_i = \begin{cases} 1 & Y_i < Low_i \\ \left(\frac{Y_i - Low_i}{High_i - Low_i}\right)^w & Low_i < Y_i < High_i \\ 0 & Y_i > High_i \end{cases} \quad (3)$$

$$D = \left(\prod_{i=1}^{n} d_i^{r_i}\right)^{1/\sum r_i} \quad (4)$$

where Y is the response factor and Low and $High$ are the minimum and maximum response values, respectively. r is the number of output responses, and w is the weight of the factors is 1 for each factor. The parameters criterion is as abovementioned in Table 2. Optimization results are depicted in Table 9 and Figure 8. The red lines in Figure 8 indicate the values in order to maximize the desirability value. The influence of each parameter on the target factor is shown by black lines. Composite desirability (D) value should be about "1" in order to be confidential which in this examination is "0.9159".

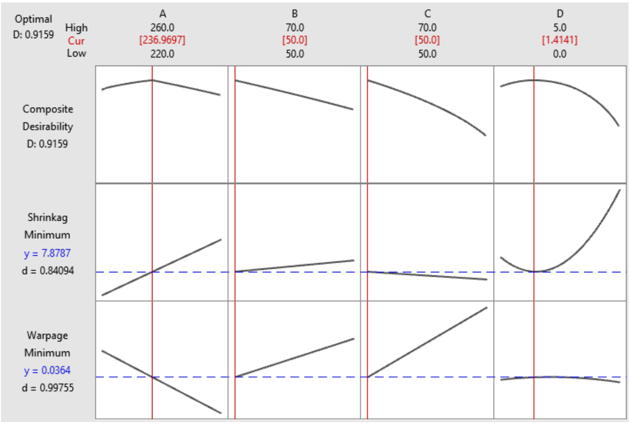

Figure 8. Optimization plot aimed at warpage and volumetric shrinkage minimization

Table 9. Optimization resultant values

Parameter	Optimized value
Melt temperature (°C)	237
Mold temperature (°C)	50
Injection pressure (MPa)	50
Nano $CaCO_3$ (%)	1.4

4. Conclusion

This paper is focused on examining and optimizing injection molding process parameters in order to produce PA6/ABS/$CaCO_3$ nanocomposite. For this purpose, injection pressure, mold temperature and melt temperature as process parameters and nano $CaCO_3$ amount as materialistic parameter are considered. In this regard, the Taguchi method and Autodesk Moldflow® software are utilized. The tests have been conducted based on orthogonal L9 array DOE. In the following, Autodesk Moldflow® software conducted the simulation process according to the established DOE. The suitable gate location was determined by Moldflow® software. The target factors include warpage and shrinkage after the part ejection. Afterwards, ANOVA was implemented to evaluate the parameters significance. Moreover, regression models with high R-Squared have been correlated. Each parameter influence on warpage and shrinkage was also studied by main effects plot. To find the optimal setting, desirability method was established. The optimum condition is found to be the injection pressure of 50 MPa, mold temperature of 50 °C, melt temperature of 237 °C and 1.4 % nano $CaCO_3$.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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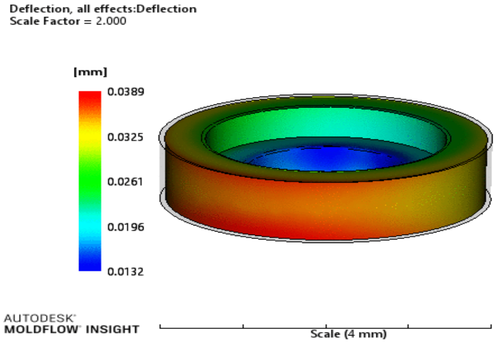
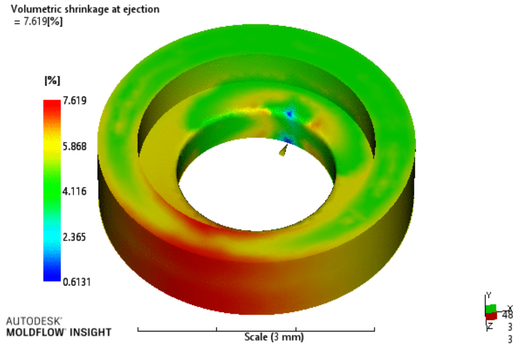
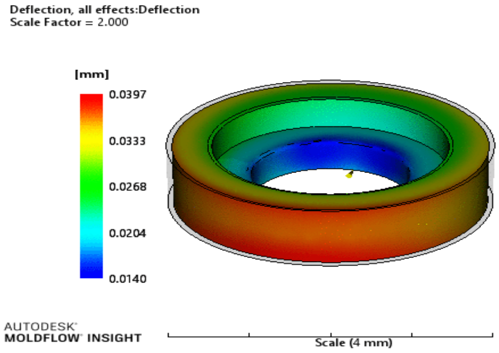
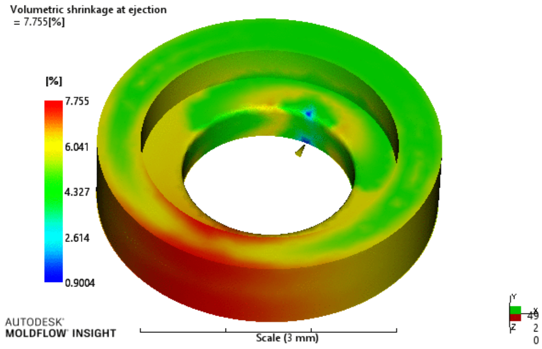
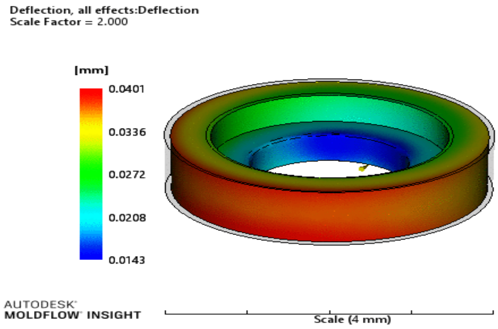
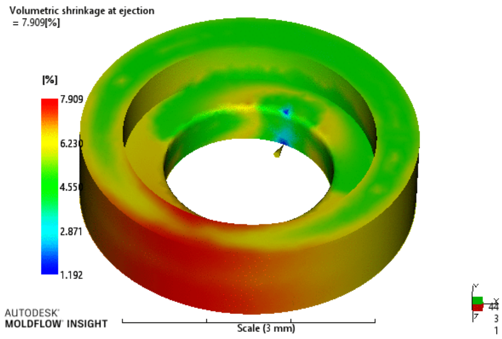
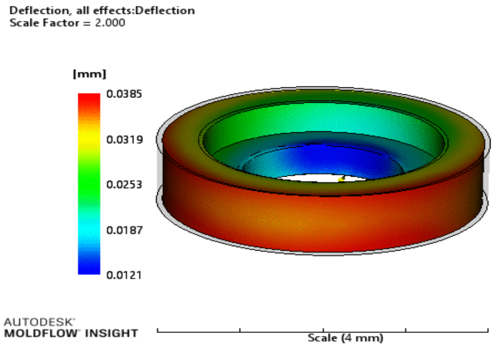
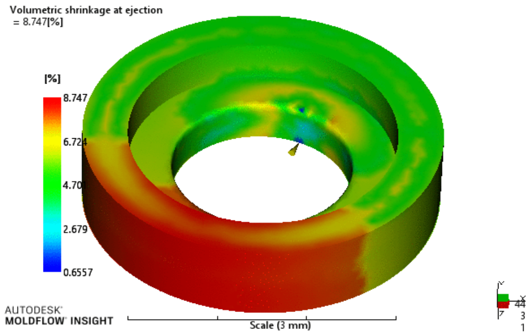
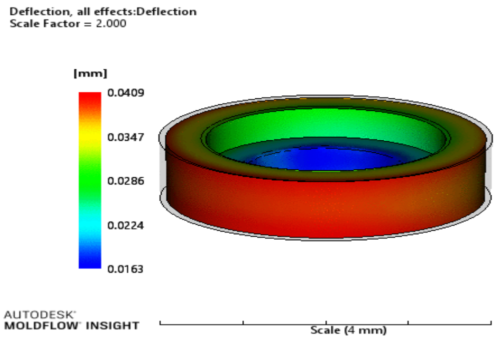
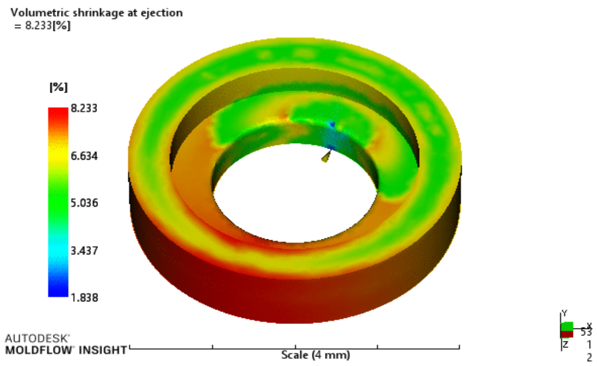
Appendix I

Table 4. Warpage and volumetric shrinkage results after simulation

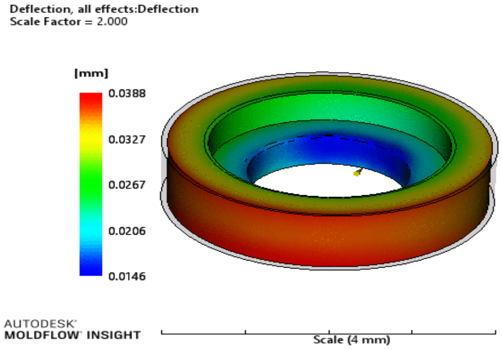
No.	Warpage (mm)	Volumetric shrinkage (%)
1		
2		
3		
4		

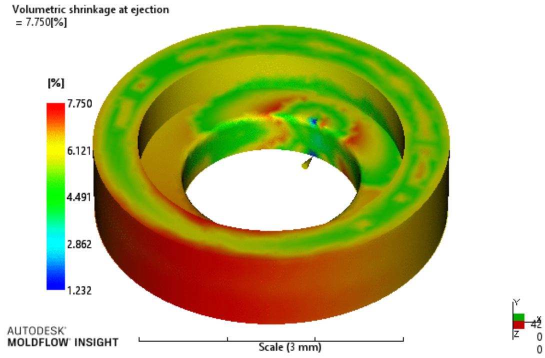
5


Deflection, all effects:Deflection
Scale Factor = 2.000
[mm]
0.0409
0.0347
0.0286
0.0224
0.0163
AUTODESK
MOLDFLOW INSIGHT
Scale (4 mm)

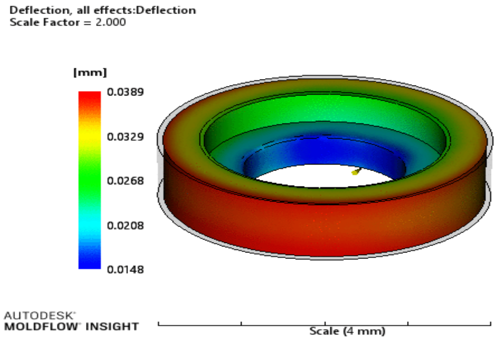

Volumetric shrinkage at ejection
= 8.233[%]
[%]
8.233
6.634
5.036
3.437
1.838
AUTODESK
MOLDFLOW INSIGHT
Scale (4 mm)

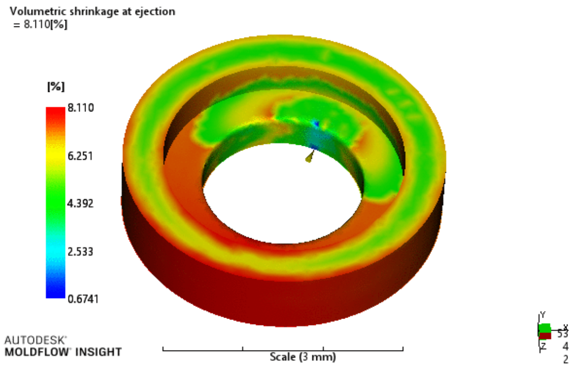
6


Deflection, all effects:Deflection
Scale Factor = 2.000
[mm]
0.0388
0.0327
0.0267
0.0206
0.0146
AUTODESK
MOLDFLOW INSIGHT
Scale (4 mm)

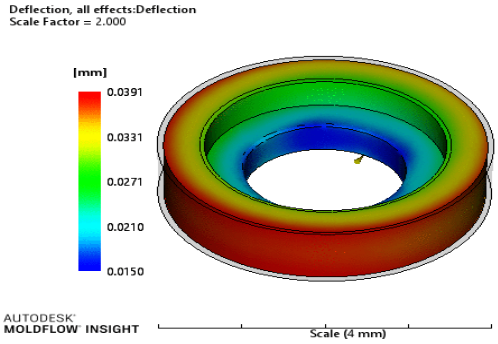

Volumetric shrinkage at ejection
= 7.750[%]
[%]
7.750
6.121
4.491
2.862
1.232
AUTODESK
MOLDFLOW INSIGHT
Scale (3 mm)

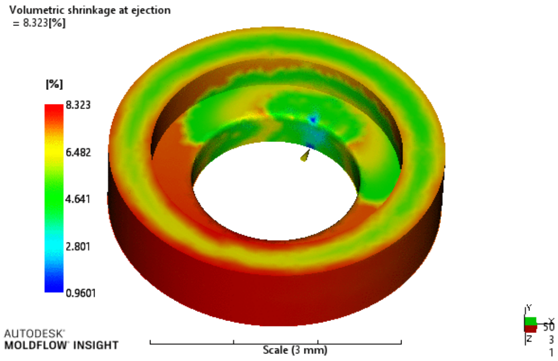
7


Deflection, all effects:Deflection
Scale Factor = 2.000
[mm]
0.0389
0.0329
0.0268
0.0208
0.0148
AUTODESK
MOLDFLOW INSIGHT
Scale (4 mm)


Volumetric shrinkage at ejection
= 8.110[%]
[%]
8.110
6.251
4.392
2.533
0.6741
AUTODESK
MOLDFLOW INSIGHT
Scale (3 mm)

8


Deflection, all effects:Deflection
Scale Factor = 2.000
[mm]
0.0391
0.0331
0.0271
0.0210
0.0150
AUTODESK
MOLDFLOW INSIGHT
Scale (4 mm)


Volumetric shrinkage at ejection
= 8.323[%]
[%]
8.323
6.482
4.641
2.801
0.9601
AUTODESK
MOLDFLOW INSIGHT
Scale (3 mm)

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