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Minimization of Shrinkage in Injection Molding Process of Acetal Polymer Gear Using Taguchi DOE Optimization and ANOVA Method

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Abstract: Injection molding is one of the very widely used manufacturing process for polymer materials due to its high production rate and low process cost. However, polymer parts manufactured through injection molding process are prone to various defects such as geometrical defect, shape related defect and visual defects. All designers work hard to minimize these defects and increase the quality of the molded part to satisfy the end application through the molding process parameters optimization with help of design of experiments (DOE). The main objective of this paper is to study the effect of various injection molding process parameters on the volumetric shrinkage of a acetal polymer gear part, identifying the most significant parameter causing high volumetric shrinkage and optimizing the process parameters through Taguchi orthogonal array design and analysis of variance (ANOVA) method. The acetal polymer gear injection molding process is simulated using Moldflow adviser ultimate simulation software and the change in volumetric shrinkage is analysed for various process parameters combination. Taguchi optimization and ANOVA method were found to be very useful in determining the most significant molding process parameter that affect volumetric shrinkage and optimizing the control parameters for achieving minimum part shrinkage.

Keywords: Injection molding, polymer gears, shrinkage, Taguchi optimization, ANOVA method.

1. INTRODUCTION

Injection molding is a well-established and well-developed manufacturing process used for the production of various plastic parts ranging from simple to complex shapes. Thermoplastics such as low density polyethylene (LDPE), high density polyethylene (HDPE) and polypropylene (PP) are the very widely used polymer materials for the production of high volume consumer goods [1]. High performance engineering thermoplastics such as acetal, nylon and PEEK are used in various gear applications as an alternate material against metal gears. Polymer gears also offers various benefits over metal gears such as weight reduction, noise reduction, torque reduction, reduced lubrication, etc [2]. Acetal also known as polyoxymethylene is one of the very widely used high performance engineering thermoplastic. Acetal is known for its high tensile strength, high stiffness, high toughness, excellent chemical resistance, low friction, etc [3]. Shrinkage is one of the major defect which occurs during the packing and cooling phase of the plastics injection molding process. The geometric reduction in the size of molded part is referred as shrinkage while the three dimensional reduction in the volume of the molded part is known as volumetric shrinkage [4]. Shrinkage cannot be eliminated completely in the injection molding process which is due to the fact that all polymers materials will undergo certain amount of contraction when it is cooled. However, shrinkage can be minimized by controlling and optimizing the injection molding process parameters such as melt temperature, mold temperature, packing time, packing pressure and cooling time [5].

The Taguchi method is one of the very widely used statistical tool for the optimization of molding process parameters which in turn help in minimizing the various process defects such as shrinkage, sink marks, warpage and high molded in stress. Taguchi method DOE also allows the designer to choose the suitable array depending upon the number of control factors and their levels [6]. The signal to noise ratio which is called as S/N ratio in short is a very powerful quality indicator in Taguchi method which evaluates any small change in the input parameters on the output variable [7].

Tuncay and et al minimized the warpage and sink marks in injection molded thermoplastic material using Taguchi optimization and ANOVA method. They also found the most significant control parameter affecting warpage and sink mark and optimised them with help of Taguchi DOE method [8]. Rishi Pareek and et al studied the effect of various injection molding process parameters on the tensile strength of a polycarbonate material. They also identified the melt temperature as the most significant control parameter for tensile strength and optimised the control parameters using Taguchi orthogonal array design and ANOVA method [9]. Mathivanan and et al studied the effect of molding variables on sink mark depth of injection molded part and found that the rib distance from the feed point as the most significant factor in minimizing the sink mark defect [10]. Nik Mizamzul and et al studied the effect of injection molding process parameters on two response variables including deflection and volumetric shrinkage of a polypropylene spur gear using grey relational analysis and ANOVA method [11].

2. SCOPE OF STUDY

The scope of this study are as follows,

1. The material chosen for this study is acetal (also called as polyoxymethylene) and the grade of material selected is Delrin 500P.

2. The control factors chosen for this study are melt temperature, mold temperature, packing time, packing pressure and cooling time.

3. The response variable chosen for this study is volumetric shrinkage

4. The volumetric shrinkage is simulated using Moldflow Adviser Ultimate software, an Autodesk product and the DOE is run using Minitab 17 software.

5. The deliverables of this study includes the identification of the most significant control factor and optimization of the control factors for achieving minimum volumetric shrinkage.

3. MATERIAL

The polymer material selected for this experimental study is Delrin acetal 500P grade, a high performance engineering polymer manufactured by DuPont. The mechanical properties of Delrin acetal 500P and its recommended molding conditions are as shown in the below tables [12]. The gear model selected for this work is 30 teeth 2 module spur gear as shown in figure 1.

Figure 1: Spur gear model with 2 module and 30 teeth configuration

Table 1: Properties of Delrin acetal 500P grade polymer

S. No.	Description	UOM	Value
1	Density	Kg/m^3	1420
2	Yield stress	MPa	70
3	Tensile modulus	MPa	3100
4	Flexural stress	MPa	80
5	Flexural modulus	MPa	2900
6	Strain at break (50mm/min)	%	40

Table 2: Recommended injection molding parameters for Delrin acetal 500P grade polymer

S. No.	Description	UOM	Value
1	Melt temperature	^{0}C	205 – 225
2	Mold temperature	^{0}C	80 – 100
3	Hold pressure	MPa	80 – 100
4	Drying temperature	^{0}C	80
5	Molding shrinkage i) Normal ii) Parallel	%	 i) 1.9 ii) 2.0

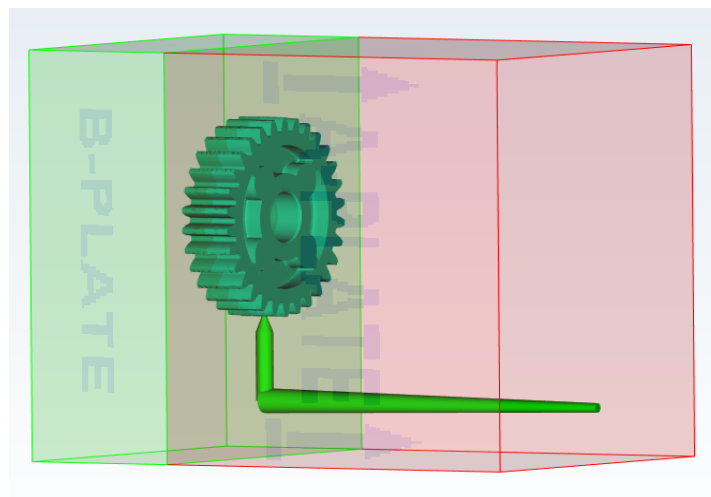**Mold Construction and Runner system design:**

Figure 2: Mold cavity and runner system

The gating system selected for this study is radial type runner system with the tapered gate end acting as the injection point on the top land of the gear teeth. Radial type gate is one of very commonly used gating system in the plastics injection molding process. The dimensions of the runner systems are shown in the below table. The mold material selected for this study is P20 steel with A-Plate assembled on the stationary side of injection molding machine while B-Plate is assembled to the moving side of the machine.

Table 3: Gating system dimensions

Runner element	Element type	Element dimensions
Sprue	Tapered	Length – 110 mm Diameter, D1 – 3 mm Diameter, D2 – 8 mm
Runner	Cold	Length – 22 mm Diameter – 5 mm
Gate	Tapered	Length – 5mm Diameter, D1 – 5 mm Diameter, D2 – 1.5 mm

Selection of Control factors and levels:

The control factors selected for this DOE are melt temperature (A), mold temperature (B), packing time (C), packing pressure (D) and cooling time (E). The upper and lower limit values for melt temperature, mold temperature and packing pressure are selected based on the recommended molding conditions for Delrin acetal 500P material grade. All the five control parameters are varied in five different levels and hence Taguchi L25 orthogonal array design is chosen for this statistical analysis.

Table 4: Selected control factors and levels

Control Factors	Levels				
	1	2	3	4	5
Melt temperature (^{0}C)	205	210	215	220	225
Mold temperature (^{0}C)	80	85	90	95	100
Packing time (sec)	10	20	30	40	50
Packing pressure (MPa)	80	85	90	95	100
Cooling time (sec)	50	60	70	80	90

Taguchi Orthogonal array design:

The L25 orthogonal array design is selected considering the five control factors and their five levels.

Table 5: Taguchi L25 Orthogonal array design

Run	Control factors				
	Melt temperature (A)	Mold temperature (B)	Packing time (C)	Packing pressure (D)	Cooling time (E)
1	205	80	10	80	50
2	205	85	20	85	60
3	205	90	30	90	70
4	205	95	40	95	80
5	205	100	50	100	90
6	210	80	20	90	80
7	210	85	30	95	90
8	210	90	40	100	50
9	210	95	50	80	60
10	210	100	10	85	70
11	215	80	30	100	60
12	215	85	40	80	70
13	215	90	50	85	80
14	215	95	10	90	90
15	215	100	20	95	50
16	220	80	40	85	90
17	220	85	50	90	50
18	220	90	10	95	60
19	220	95	20	100	70
20	220	100	30	80	80
21	225	80	50	95	70
22	225	85	10	100	80
23	225	90	20	80	90
24	225	95	30	85	50
25	225	100	40	90	60

The injection molding simulation is performed in the Moldflow adviser software for 25 runs as per table 5 and the values of volumetric shrinkage is noted as the response for which the signal to noise ratio (S/N ratios) is calculated. The type of S/N ratio chosen for this study is "smaller the better" as the objective is to minimize the volumetric shrinkage.

Table 6: S/N ratio for volumetric shrinkage as response parameter

| Run	Control factors					Response	S/N ratio
	Melt temperature (A)	Mold temperature (B)	Packing time (C)	Packing pressure (D)	Cooling time (E)	Volumetric shrinkage	SNRA1
1	205	80	10	80	50	17.93	-25.07161
2	205	85	20	85	60	17.87	-25.04249
3	205	90	30	90	70	17.74	-24.97907
4	205	95	40	95	80	17.66	-24.93981
5	205	100	50	100	90	17.57	-24.89544
6	210	80	20	90	80	18.15	-25.17753
7	210	85	30	95	90	18.03	-25.11991
8	210	90	40	100	50	17.96	-25.08613
9	210	95	50	80	60	18.17	-25.1871
10	210	100	10	85	70	18.22	-25.21097
11	215	80	30	100	60	18.31	-25.25377
12	215	85	40	80	70	18.66	-25.41823
13	215	90	50	85	80	18.56	-25.37156
14	215	95	10	90	90	18.65	-25.41358
15	215	100	20	95	50	18.35	-25.27272
16	220	80	40	85	90	18.94	-25.5476
17	220	85	50	90	50	18.81	-25.48778
18	220	90	10	95	60	18.92	-25.53842
19	220	95	20	100	70	18.66	-25.41823
20	220	100	30	80	80	19	-25.57507
21	225	80	50	95	70	19.08	-25.61157
22	225	85	10	100	80	19.28	-25.70214
23	225	90	20	80	90	19.33	-25.72913
24	225	95	30	85	50	19.26	-25.69313
25	225	100	40	90	60	19.2	-25.66602
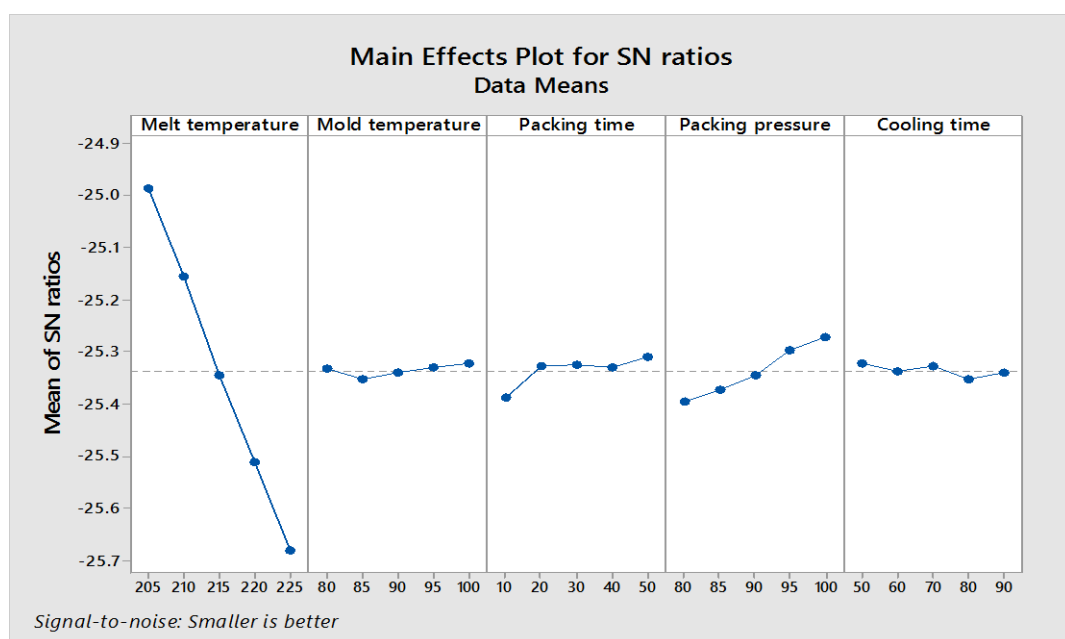
Figure 3: Main effects plot for SN ratios

From the main effects plot for S/N ratios "smaller the better" as shown in figure 3 it can be determined the best parameters combination for minimum volumetric shrinkage is A1-B5-C5-D5-E1 and similarly the worst parameters combination that would result in maximum volumetric shrinkage is A5-B2-C1-D1-E4.
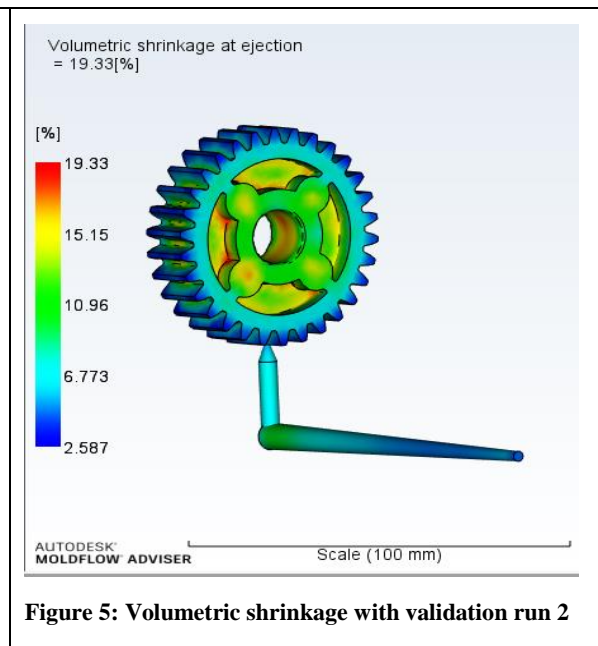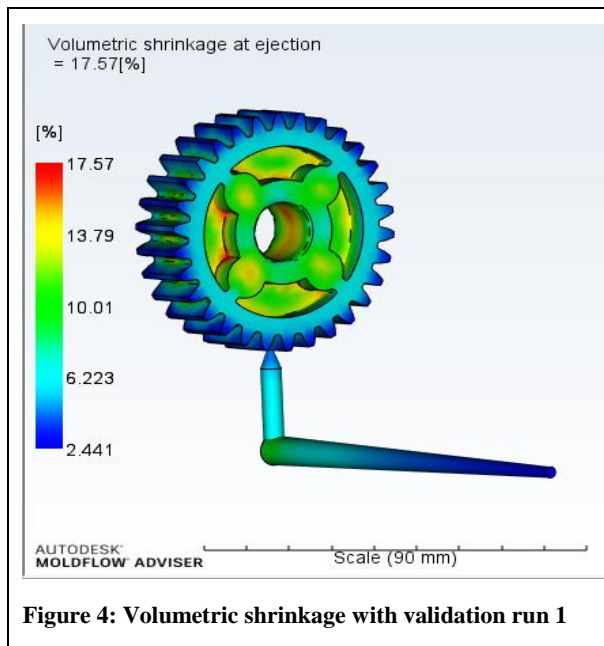
Table 7: Validation run for volumetric shrinkage

Validation run	Melt temperature	Mold temperature	Packing time	Packing pressure	Cooling time	Volumetric shrinkage
1	205	100	50	100	50	17.57
2	225	85	10	80	80	19.33

Table 8: Taguchi DOE Vs Moldflow simulation result validation

Process parameters combination	DOE Prediction (using Minitab)	Moldflow simulation prediction	% Error margin
Minimum volumetric shrinkage	17.51	17.57	0.34
Maximum volumetric shrinkage	19.54	19.33	1.07

However, the best parameters combination for minimum volumetric shrinkage and worst parameters combination for maximum volumetric shrinkage are not included in the Taguchi L25 DOE array and hence validation run is performed for those two combinations in the Minitab software and as well in the Moldflow adviser software. From the above validation run in table 7 and 8, the optimum process parameters combination for achieving minimum volumetric shrinkage are melt temperature 205^0C, mold temperature 100^0C, packing time 50 sec, packing pressure 100 MPa and cooling time 50 sec. The minimum and maximum volumetric shrinkage prediction by Minitab software seems to be in line with the Moldflow adviser prediction with minimum error margin. This validates the effectiveness of using Taguchi DOE technique in determining the optimum level of control factors for achieving minimum part shrinkage.

| **Figure 4: Volumetric shrinkage with validation run 1** | **Figure 5: Volumetric shrinkage with validation run 2** |

The simulated volumetric shrinkage at ejection for validation parameters are shown in figure 4 and 5. It can be observed that the minimum and maximum volumetric shrinkage of the simulated polymer gears are lower for the process parameters listed in validation run 1 which refers to the optimum parameters combination for achieving the lower volumetric shrinkage. In case of simulation with parameters combination of validation run 1, the minimum shrinkage on teeth regions is 2.44% while the maximum shrinkage in between the teeth and hub regions is 17.57%. In case of simulation with parameters combination of validation run 2, the minimum shrinkage on teeth regions is 2.58% while the maximum shrinkage in between the teeth and hub regions is 19.33%. The volumetric shrinkage is lower by 1.76% in case of validation run 1 as compared with validation run 2. This volumetric shrinkage comparison through validation run confirms the optimum process parameters of melt temperature 205 ^{0}C, mold temperature 100 ^{0}C, packing time 50 sec, packing pressure 100 MPa and cooling time 50 sec as the best combination. Also the below response table for S/N ratios

confirms the melt temperature as the most significant process parameter with rank 1, followed by packing pressure as rank 2, packing time as rank 3, cooling time as rank 4 and mold temperature as rank 5.

```
Response Table for Signal to Noise Ratios
Smaller is better

             Melt        Mold    Packing   Packing   Cooling
Level  temperature  temperature     time   pressure      time
1          -24.99      -25.33    -25.39     -25.40    -25.32
2          -25.16      -25.35    -25.33     -25.37    -25.34
3          -25.35      -25.34    -25.32     -25.34    -25.33
4          -25.51      -25.33    -25.33     -25.30    -25.35
5          -25.68      -25.32    -25.31     -25.27    -25.34
Delta        0.69        0.03      0.08       0.13      0.03
Rank            1           5         3          2         4
```

Figure 6: Response table for S/N ratios

The percentage contribution of each control parameter on the response variable (i.e.) volumetric shrinkage is calculated using the method of analysis of variance as per table 9 in which the f is degree of freedom, S is the sum of squares, V is the value of variance, F is the F-ratio and P is the percentage contribution.

Table 9: Analysis of variance for volumetric shrinkage

Control Factors	f	S	V	F	P (%)
Melt temperature	4	6.90654	1.726640	839.8	95.12%
Mold temperature	4	0.01202	0.003010	1.46	0.17%
Packing time	4	0.07770	0.019430	9.45	1.07%
Packing pressure	4	0.24170	0.060430	29.39	3.33%
Cooling time	4	0.01470	0.003680	1.79	0.20%
Error	4	0.00822	0.002060		0.11%
Total	24	7.26090			100.00%

From the above ANOVA table, it was found that the most significant control parameter which affects volumetric shrinkage is the melt temperature contributing about 95.12% followed by packing pressure which contributes to 3.33%. The other parameters including packing time, mold temperature and cooling time were found to be insignificant and have very negligible effect on the volumetric shrinkage.

4. CONCLUSION

The design of experiments through Taguchi orthogonal array and analysis of variance method found to be very useful in determining the significant process parameter having the maximum effect on the response variable volumetric shrinkage and also helped in optimizing the control parameters for achieving minimum volumetric shrinkage. For acetal polymer gear injection molding, the melt temperature is having the highest percentage contribution on the volumetric shrinkage followed by the packing pressure. For achieving minimum volumetric shrinkage, it is recommended to operate with the lower limit of melt temperature (i.e.) 205^0C and upper limit of packing pressure (i.e.) 100 MPa.

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