International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:13, No:2, 2019

Optimization of Two Quality Characteristics in Injection Molding Processes via Taguchi Methodology

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Abstract**—**The main objective of this research is to optimize tensile strength and dimensional accuracy in injection molding processes using Taguchi Parameter Design. An L16 orthogonal array (OA) is used in Taguchi experimental design with five control factors at four levels each and with non-controllable factor vibration. A total of 32 experiments were designed to obtain the optimal parameter setting for the process. The optimal parameters identified for the shrinkage are shot volume, 1.7 cubic inch (A4); mold term temperature, 130 ºF (B1); hold pressure, 3200 Psi (C4); injection speed, 0.61 inch3/sec (D2); and hold time of 14 seconds (E2). The optimal parameters identified for the tensile strength are shot volume, 1.7 cubic inch (A4); mold temperature, 160 ºF (B4); hold pressure, 3100 Psi (C3); injection speed, 0.69 inch3/sec (D4); and hold time of 14 seconds (E2). The Taguchi-based optimization framework was systematically and successfully implemented to obtain an adjusted optimal setting in this research. The mean shrinkage of the confirmation runs is 0.0031%, and the tensile strength value was found to be 3148.1 psi. Both outcomes are far better results from the baseline, and defects have been further reduced in injection molding processes.

Keywords**—**Injection molding processes, Taguchi Parameter Design, tensile strength, shrinkage test, high-density polyethylene, HDPE.

I. Introduction

INJECTION molding is a manufacturing process used to produce parts by injecting raw plastic material into a mold cavity of desired shapes [1]. It is a cost-effective method to produce plastic parts in mass production. With injection molding processes, plastic parts can be produced with low variability and fewer defects. A variety of raw materials can be processed in injection molding process, such as thermoplastics like polyethylene, polypropylene, Delrin, etc. The quality of the injection molded part mostly depends on material properties, mold design, and process parameters. Since the material is fixed for a specific type of product, more emphasis is required on mold design and process parameters. A slight change in significant parameters may result in the production of more defective parts. Two examples of defects are shrinkage error and low tensile strength. Shrinkage error in the plastics will result in dimensional instability which leads to inaccurate parts. Low tensile strength leads to breakage of the parts under the influence of stress or sudden shock loads.

This research is focused on improving the tensile strength and reducing shrinkage of polyethylene specimen by using Taguchi orthogonal design to find out the best parameter settings in injection process. Taguchi method is a very useful technique used to achieve higher quality and reduce the cost of the product [2]. Table I shows the summary of the researches using Taguchi method to improve and optimize the performance of injection molding process. Most of the researchers focused on optimizing one quality characteristic, and this research is focused on optimizing two quality characteristics by selecting and optimizing one set of process parameters. Parameters that could affect the above two quality characteristics are mold temperature, melt temperature, injection pressure, injection time, injection speed, shot volume, packing pressure, packing time, cooling time, metering stroke, and barrel temperature.

II. The Experimental Design

The experiment was carried out on an Engel Injection molding machine. Fig. 1 gives the shape and dimensions of the specimen [3]. High-Density Polyethylene (HDPE) Resin from Dow Chemical Company is used as raw material. Tensile strength and shrinkage are selected as response variables. Tensile strength and shrinkage are selected as quality characteristics (QC) variables.

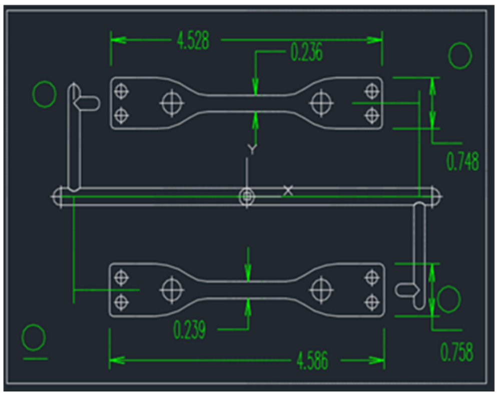

Fig. 1 The specimen of this study

For tensile strength (QC1), shot volume, injection speed, mold temperature, cooling time are the key control factors. It is tested by the tensile testing machine Intron MTS. And

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shrinkage (QC2) is calculated with the following equation.

$$S= (L_m\, W_m - L_p\, W_p)/\, L_m\, W_m \times 100\%$$

where S= Shrinkage error percentage, L_m = Length of Mold, L_p = Length of Part, W_m = Width of the Mold, $W_{p=}$ Width of Part.

TABLE I
SUMMARY OF PREVIOUS RESEARCHERS

S.no	Author/Year	Parameters	Performance Measures	Remark	Technique used
1	*Annicchiarico & Alcock -2014* [4]	1) Cooling Time 2)Packing pressure 3)Packing time 4) Melt temperature 5)Mold temperature 6)Injection speed 7) Barrel temperature	Shrinkage, sink marks, voids	The paper is aimed to analyze the all the factors that affect the shrinkage, in terms of design, parameters, process, materials level. Didn't specify how to measure shrinkage.	Literature survey
2	*Kamaruddin et al.-2010* [5]	1) Injection speed 2)Melt temperature 3) Injection pressure 4)Packing Pressure 5)packing time 6) cooling time	Shrinkage	This paper concludes, Low melting temperature, high injection pressure, low packing pressure, low packing time, and long cooling time will result in less shrinkage	Taguchi, ANOVA, DOE
3	*Hussin et al.-2015* [6]	1) Mold Temperature 2) Melt temperature 3) Packing Pressure 4) Packing time 5) Cooling Time	Shrinkage	Cooling time is the least contributing factor for the shrinkage	Taguchi Method, Mold Flow plastic insight software.
4	*Chen et al.-2015* [7]	1) Melt Temperature 2) Injection speed 3) Packing Pressure 4) Packing Time 5) Cooling time	Shrinkage Warpage	At a Fixed cooling time, the warpage decreased better, while the packing time increased. Packing pressure had more significant influence on the warpage and length.	Taguchi, ANOVA, Response surface Methodology
5	*Akbarzadeh and Sadeghi- 2011* [8]	1) Melt Temperature 2) Packing pressure 3) Injection Pressure 4) Packing Time 5) Cooling time	Shrinkage	Injection pressure is not statistically significant on polypropylene material	Invasive Weed Optimization (IWO) algorithm
6	*Mehat et al.-2012* [9]	1) Melt Temperature 2) Packing pressure 3) Packing Time 4) Cooling time	Shrinkage	Melt temperature showed the strongest effect on shrinkage	Grey-Based-Taguchi Optimization Method
7	*Alam and Kumar- 2013* [10]	1) Mold Temperature 2) Melt temperature 3) Packing Pressure 4) Packing time	Shrinkage	Packing pressure was found most effective factor for PP followed by packing time, injection pressure and melt temperature.	Taguchi Method
8	*Zaboj-2015* [11]	1)Mold Temperature 2)Melt temperature 3)Injection rate 4) Holding pressure	Shrinkage	Shrinkage increases with the length in the direction of the flow, high packing pressure and melt temperature decreased shrinkage	
9	*Chang and Faison* [3]	1) Mold temperature 2) Melt temperature 3) Holding pressure 4) Holding time	Shrinkage	The control factor play crucial role in reducing shrinkage	Taguchi method

III. TAGUCHI PARAMETER DESIGN

The Taguchi method is identified for its robust engineering. The idea behind the robust design is to improve the quality of a product by minimizing the effects of variation without eliminating the causes [12]. Taguchi design is mainly based on two kinds of factors: controllable factors, and non-controllable factors. Controllable factors in this research are shot volume, mold temperature, injection speed, hold pressure and hold time. Non-controllable parameters are noise factors. Taguchi method uses signal to noise (S/N) ratio to measure the performance of QC. Three different objective functions can be used in Taguchi method to optimize the response variable [13].

Smaller the better $$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

Nominal the better $$\frac{S}{N} = 10\log\left(\frac{\left(\frac{1}{n}\sum_{i=1}^{n} y_i\right)^2}{S_y^2}\right) \quad (2)$$

Larger the better $$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (3)$$

where y_i is the result of the observed value, and n is the number of times that the experiment is repeated [13]. In our research case, to measure the QC1, we choose the smaller the better case and for QC2, we choose the larger the better case.

Baseline Analysis

The baseline parameters selected for this research are mold temperature (MF) (140 °F), shot volume (SV) (1.5 inches/cc), holding pressure (HP) (3000 psi), injection speed (IS) (0.61 $inch^3$/sec), holding time (HT) (14 sec) and vibration (Vibe), and non-vibration (N-Vibe) is considered as noise factor. The results of the baseline parameters are in Table II.

TABLE II
BASELINE PARAMETER RESULTS

S.no	1	2	3	4	5	6	7	8	9	10	Average
Tensile strength (PSI)	3080	3013	3090	2678	3177	2519	2937	2717	2735	3138	2908.4
Shrinkage error	1.69	2.37	2.03	1.87	2.31	2.15	2.25	2.24	2.56	2.20	2.17

OA Design

After selecting the control factors and noise factors, the next important thing is designing the Taguchi parameters and the levels for the experiment. To widen the scope of the research and give more access to parameters levels, an L16 OA with five parameters and four levels is selected for this research. Table III shows the controllable parameters with four levels and uncontrollable factors which are vibration. The reason for selecting vibration is that it is most likely present in all the manufacturing shop floors.

TABLE III
PARAMETER DESIGN

	Variable	**Unit**	**Levels**			
			1	2	3	4
A	Shot volume (SV)	in/cc	1.4	1.5	1.6	1.7
B	Mold temperature (MT)	Fahrenheit	130	140	150	160
C	Hold pressure (HP)	Psi	2900	3000	3100	3200
D	Injection speed (IS)	$inch^3$ / sec	0.57	0.61	0.65	0.69
E	Hold time (HT)	seconds	12	14	16	18
Non- Controllable Factors						
1	Vibration					
2	No vibration					
OC	Tensile strength (QC1)		Shrinkage (QC2)			

TABLE IV
L_{16} ORTHOGONAL DESIGN

N	**Factor** A (SV)	B (MT)	C (HP)	D (IS)	E (HT)	**Noise factors** Vibration	
1	1	1	1	1	1	On	Off
2	1	2	2	2	2	On	Off
3	1	3	3	3	3	On	Off
4	1	4	4	4	4	On	Off
5	2	1	2	3	4	On	Off
6	2	2	1	4	3	On	Off
7	2	3	4	1	2	On	Off
8	2	4	3	2	1	On	Off
9	3	1	3	4	2	On	Off
10	3	2	4	3	1	On	Off
11	3	3	1	2	4	On	Off
12	3	4	2	1	3	On	Off
13	4	1	4	2	3	On	Off
14	4	2	3	1	4	On	Off
15	4	3	2	4	1	On	Off
16	4	4	1	3	2	On	Off

In this research, the OA will be L16. The OA is based on a number of control factors known as the 5, and their levels, known as the 4. Thus, L_{16} represents 16 experiments that should be done to study five factors at four different levels for adequate experimental analysis. Table IV shows the experiment designed using OA L_{16}.

TABLE V
EXPERIMENTAL RESULTS FOR SHRINKAGE ERROR – QC1

N	Control Factors					Noise factors				Response	
	A-SC	B-MT	C-HP	D-IP	E-HT	Vibration		No vibration		mean	S/N Ratio
1	1(1.4)	1(130)	1(2900)	1(0.57)	1(12)	1.9517	1.9830	2.2919	2.1900	2.1042	-9.4916
2	1(1.4)	2(140)	2(3000)	2(0.61)	2(14)	1.7390	1.7859	2.1264	2.1400	1.9478	-8.8408
3	1(1.4)	3(150)	3(3100)	3(0.65)	3(16)	2.2929	2.2354	2.2028	2.2187	2.2375	-10.0064
4	1(1.4)	4(160)	4(3200)	4(0.69)	4(18)	2.4564	2.5498	2.3791	2.3267	2.4280	-10.7205
5	2(1.5)	1(130)	2(3000)	3(0.65)	4(18)	2.0281	2.0978	2.0163	2.0934	2.0589	-9.2844
6	2(1.5)	2(140)	1(2900)	4(0.69)	3(16)	2.0264	2.0165	2.1492	2.1256	2.0794	-9.3726
7	2(1.5)	3(150)	4(3200)	1(0.57)	2(14)	2.4029	2.3946	1.9478	1.9865	2.1829	-9.8336
8	2(1.5)	4(160)	3(3100)	2(0.61)	1(12)	2.1155	2.0912	2.2567	2.2945	2.1895	-9.8240
9	3(1.6)	1(130)	3(3100)	4(0.69)	2(14)	0.0669	0.0897	1.3764	1.3260	0.7148	-2.6307
10	3(1.6)	2(140)	4(3200)	3(0.65)	1(12)	1.2000	1.3470	1.1443	1.1534	1.2112	-4.6940
11	3(1.6)	3(150)	1(2900)	2(0.61)	4(18)	1.5197	1.6479	1.2652	1.2980	1.4327	-6.1860
12	3(1.6)	4(160)	2(3000)	1(0.57)	3(16)	1.5745	1.5897	1.4861	1.5004	1.5377	-6.7513
13	4(1.7)	1(130)	4(3200)	2(0.61)	3(16)	0.7333	0.7230	0.7039	0.7032	0.7159	-0.1083
14	4(1.7)	2(140)	3(3100)	1(0.57)	4(18)	1.1333	1.1567	-0.0333	0.0023	0.5647	-1.1785
15	4(1.7)	3(150)	2(3000)	4(0.69)	1(12)	1.1004	1.2154	-0.2667	0.1998	0.5622	-1.4598
16	4(1.7)	4(160)	1(2900)	3(0.65)	2(14)	1.2667	1.2786	0.0222	0.0289	0.6491	-2.0959

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:13, No:2, 2019

TABLE VI
EXPERIMENTAL RESULTS FOR TENSILE STRENGTH – QC2

Control Factors						Noise factors				Response	
N	A-SC	B-MT	C-HP	D-IP	E-HT	Vibration		No vibration		mean	S/N Ratio
1	1(1.4)	1(130)	1(2900)	1(0.57)	1(12)	2998.0	2975.0	2938.0	3128.0	3009.8	69.7
2	1(1.4)	2(140)	2(3000)	2(0.61)	2(14)	2940.0	2908.0	2997.0	3128.0	2993.3	69.6
3	1(1.4)	3(150)	3(3100)	3(0.65)	3(16)	3003.0	2994.0	3194.0	3157.0	3087.0	69.7
4	1(1.4)	4(160)	4(3200)	4(0.69)	4(18)	3002.0	3042.0	3017.0	3147.0	3052.0	69.8
5	2(1.5)	1(130)	2(3000)	3(0.65)	4(18)	2980.0	3004.0	2968.0	3109.0	3015.3	69.7
6	2(1.5)	2(140)	1(2900)	4(0.69)	3(16)	3034.0	3013.0	3076.0	3138.0	3065.3	69.8
7	2(1.5)	3(150)	4(3200)	1(0.57)	2(14)	3021.0	3052.0	3096.0	3214.0	3095.8	69.9
8	2(1.5)	4(160)	3(3100)	2(0.61)	1(12)	3040.0	3190.0	3115.0	3214.0	3139.8	70.1
9	3(1.6)	1(130)	3(3100)	4(0.69)	2(14)	3195.0	3205.0	3214.0	3166.0	3195.0	70.1
10	3(1.6)	2(140)	4(3200)	3(0.65)	1(12)	3094.0	3128.0	3135.0	3028.0	3096.3	69.8
11	3(1.6)	3(150)	1(2900)	2(0.61)	4(18)	3099.0	3128.0	3115.0	3185.0	3131.8	70.0
12	3(1.6)	4(160)	2(3000)	1(0.57)	3(16)	3190.0	3157.0	3233.0	3128.0	3177.0	69.9
13	4(1.7)	1(130)	4(3200)	2(0.61)	3(16)	3390.0	3310.0	3369.0	3262.0	3332.8	70.3
14	4(1.7)	2(140)	3(3100)	1(0.57)	4(18)	3182.0	3281.0	3351.0	3319.0	3283.3	70.4
15	4(1.7)	3(150)	2(3000)	4(0.69)	1(12)	3390.0	3338.0	3391.0	3434.0	3388.3	70.6
16	4(1.7)	4(160)	1(2900)	3(0.65)	2(14)	3423.0	3396.0	3302.0	3453.0	3393.5	70.7

IV. TAGUCHI ANALYSIS AND DISCUSSION

In this section, a study on the effects of the shot volume, mold temperature, hold pressure, injection speed, and hold time on the tensile strength and shrinkage using the Taguchi Parameter design approach is analyzed. All experimental measurements are recorded in Tables V and VI. The mean values for all runs are calculated. Since, this research attempts to seek a parameters setting which enables the injection molding process to produce parts with minimal shrinkage error, therefore, (1) is given to define S/N ratio values as shown in Table V. The other attempt of this research is to maximize the tensile strength for the injection molded parts, thus, (3) is given to define S/N values as shown in Table VI.

Data and Noise Factor Analysis for Shrinkage

Tables VII and VIII provide some insights of the relationship between the control factors and the shrinkage error. They are summarized as follows: (a) shot volume has a significant effect in reducing the shrinkage error; (b) when mold temperature is low, it seems that the shrinkage error reduces; (c) holding pressure seems to have little effect on the shrinkage error; (d) injection speed also showed having reasonable effect on reducing the shrinkage error; and (e) hold time has little effect on the shrinkage error. The optimal parameters for the low shrinkage are the fourth level of shot Volume (A4), first level of mold temperature (B1), third level of holding pressure (C3), fourth level of injection speed (D4), and first level of holding time (E1).

TABLE VII
RESPONSE TABLE FOR MEAN OF SHRINKAGE ERROR

Level	A(SV)	B(MT)	C(HP)	D(IS)	E(HT)
1	2.1794	1.3984	1.57	1.597	1.517
2	2.1277	1.4508	1.53	1.571	1.374
3	1.2241	1.6038	1.43	1.539	1.952
4	0.623	1.7011	1.63	1.446	1.621

TABLE VIII
RESPONSE TABLE FOR S/N RATIO OF SHRINKAGE ERROR

Level	A(SV)	B(MT)	C(HP)	D(IS)	E(HT)
1	-9.7648	-5.379	-6.79	-6.814	-6.367
2	-9.5786	-6.021	-6.58	-6.24	-5.85
3	-5.0655	-6.871	-5.91	-6.52	-6.56
4	-1.2106	-7.348	-6.34	-6.046	-6.842

After completing the optimization for shrinkage, a hypothesis test for the noise factor is conducted to determine if vibration has any effect on the shrinkage. The Hypothesis test is conducted using (4). Hypotheses:

$$H_0: \mu_{S\,(\text{vibration On})} = \mu_{S\,(\text{vibration off})}$$
$$H_1: \mu_{S\,(\text{vibration on})} \neq \mu_{S\,(\text{vibration off})}$$

where μ_S = Mean of the Shrinkage with vibration on and off obtained from Table VI.

$$t = \frac{\bar{\mu}_{s(\text{vibration On})} - \bar{\mu}_{s(\text{vibration Off})}}{\sqrt{\frac{s^2_{a\,(\text{vibration On})} + s^2_{s\,(\text{vibration Off})}}{n_1 + n_2}}} \quad (4)$$

The t-value for shrinkage is 0.74 which is smaller than t critical value (with alpha = 0.01, the degree of freedom =30) which equals 2.46. So, we fail to reject the null hypothesis. This concludes that the vibration does not affect shrinkage. So, the recommended optimal setting for the process is to set vibration to “off”

Data and Noise Factor Analysis for Tensile Strength

Tables IX and X provide some insights of the relationship between the control factors and the tensile strength of the products. They are summarized as: (a) shot volume has a significant effect in increasing tensile strength; (b) when mold temperature increases, tensile strength increases; (c) holding pressure seems to have little effect on the tensile strength; (d) injection speed also showed having reasonable effect on increasing the tensile strength; and (e) hold time has little effect on the tensile strength. The optimal parameters based on abovementioned analysis are fourth level of Shot volume (A_4), the fourth level of mold temperature (B_4), the third level of the hold pressure (C_3), the fourth level of injection speed (D_4), and second level of hold time (E_2).

TABLE IX
RESPONSE TABLE FOR MEAN OF TENSILE STRENGTH

Level	A(SV)	B(MT)	C(HP)	D(IS)	E(HT)
1	3035.5	3138.1875	3150.063	3141.438	3158.5
2	3079	3109.5	3143.438	3149.375	3169.375
3	3150	3175.6875	3176.25	3148	3165.5
4	3349.438	3190.5625	3144.188	3175.125	3120.563

TABLE X
S/N TABLE FOR MEAN OF TENSILE STRENGTH

Level	A(SV)	B(MT)	C(HP)	D(IS)	E(HT)
1	69.7041	69.9446	70.0273	69.9769	70.0358
2	69.8681	69.8655	69.9535	70.0003	70.0604
3	69.9383	70.0585	70.0726	69.9757	69.9450
4	70.4962	70.1381	69.9533	70.0538	69.9654

After completing the optimization for tensile test, a hypothesis test for the noise factor is conducted to determine if vibration has any effect on the tensile strength. The hypothesis test is the same as shrinkage's test.

The t-value for tensile strength is 2.07 which is smaller than t critical value (with alpha = 0.01, the degree of freedom =30) which equals 2.46. So, we fail to reject the null hypothesis. This concludes that the vibration does not affect tensile strength. So, the recommended optimal setting for the process is to set vibration to "off". After analyzing the data for shrinkage and tensile strength, the parameter levels were not identical. Shrinkage had two optimal settings OP1 is A4, B1, C3, D4, E1 and OP2 A4, B1, C4, D2, E2. Tensile strength had one optimum setting of A4, B4, C3, D4, and E2. Hence, three confirmation runs are needed for each one uses its own parameter level setting. The three confirmation runs are presented in the next step.

V. CONFIRMATION RUNS

After getting the optimized values, confirmation runs should be conducted to ensure that optimized values have some improvement in the tensile strength and shrinkage. In this research conformation runs were used to validate than an improvement for the both and shrinkage and tensile strength is achieved.

The mean shrinkage of OP1 is 0.115 and ST Dev is 0.741 and mean shrinkage of OP2 is 0.019 and ST Dev is 0.324 which is closer to the part specifications. Hence, OP2 settings are selected as optimal parameters.

Based on the optimal setting (A4, B1, C4, D2, and E2) defined by shrinkage, the predicted optimal value for the shrinkage of the injection molding process is given as: Predicted $\mu_S = \mu_{A4} + \mu_{B1} + \mu_{C4} + \mu_{D2} + \mu_{E2} - 4*(\text{Y-Avg})_S = 0.059\%$

Based on the optimal setting (A4, B4, C3, D4, and E2) defined by tensile strength, the predicted optimal value for the tensile strength of the injection molding process is given as: Predicted $\mu_T = \mu_{A4} + \mu_{B4} + \mu_{C3} + \mu_{D4} + \mu_{E2} - 4*(\text{Y-Avg})_T = 3446.8$ Psi.

The predicted value for the tensile strength is 3446.8 Psi, but the mean of the conformation runs is 3204 psi. The mean falls between the control limits but did not reach the predicted value.

VI. FURTHER ANALYSIS

In this stage, the research focuses on discovering one optimal parameter setting for both shrinkage and tensile strength. The optimal parameter for shrinkage was (A4, B1, C4, D2, and E2) while for Tensile strength it was A4, B4, C3, D4, and E2.

The T-test was used to find if there is a difference in mean between the µS collected from the optimized parameter level for shrinkage and the µST collected from the optimized parameter level for Tensile strength. The hypothesis is defined as follows.

- H_0: $\mu_{S\ (OP2\text{-}Shrinkage)} = \mu_{ST\ (OP\text{-}Tensile\ strength)}$
- H_1: $\mu_{S\ (OP2\text{-}Shrinkage} \neq \mu_{ST\ (Op\text{-}Tensile\ strength)}$

where μ_S (OP2-Shrinkage) is the mean of the μ_S collected from running experiments using the optimized shrinkage parameter level settings, and μ_{ST} (OP-Tensile strength) is the mean of the μ_S collected from running experiments using the optimized Tensile strength parameter level settings.

The t-value is -4.25 which falls outside of t-critical value (with alpha=0.01 degree of freedom=17) which equals ±2.57. Thus, the null hypothesis is rejected. In conclusion, this result means that the non-identical parameters do affect shrinkage. And now we will take the data for tensile strength for the optimum parameters for shrinkage and tensile strength and run tests. The T-test was used to find if there is a difference in mean between the µT collected from the optimized parameter level for shrinkage and the µTS collected from the optimized parameter level for tensile strength. The hypothesis is defined as follows.

- H_0: $\mu_{T\ (OP\text{-}Tensile\ strength)} = \mu_{TS\ (OP2\text{-}Shrinkage)}$
- H_1: $\mu_{T\ (OP\text{-}Tensile\ strength)} \neq \mu_{TS\ (OP2\text{-}Shrinkage)}$

where µT (OP-Tensile strength) is the mean of the µT collected from running experiments using the optimized tensile strength parameter level settings, and µs µTS (OP2-Shrinkage) is the mean of the µTS collected from running experiments using the optimized shrinkage parameter level settings.

The T-test is analyzed with a t-value of -5.21 which falls outside of t-critical value (with alpha=0.01 degree of freedom =17) which equals ±2.57. Thus, the null hypothesis is rejected. In conclusion, this result means that the non-identical parameters do affect tensile strength.

It was found from the T-test that both null hypotheses were rejected; this means that one final run was conducted using the adjusted non-identical parameter level settings. Table XI shows the data collected from the final run measuring the shrinkage and tensile strength with the newly adjusted parameter settings shot volume of 1.7 Cubic Inch, Mold Temp

145 ºF (average of 2nd level 140 ºF and 3rd level 150 ºF), Hold Pressure 3150 Psi (average of 3rd level 3100 psi and 4 th level 3200 psi), Injection speed 0.65 Cubic inch/sec, Hold time 14 seconds are the parameter levels. The data were then further compared in another T-test to the data collected from the confirmation runs made using each separately optimized parameter level setting.

TABLE XI
FINAL RUNS WITH AN ADJUSTED PARAMETER FOR SHRINKAGE AND TENSILE STRENGTH

no	1	2	3	4	5	6	7	8	9	10	Average
Shrinkage error %	0.30	0.36	0.32	0.43	0.21	0.30	0.40	0.15	0.25	0.40	0.31
Tensile strength	3151	3160	3160	3122	3113	3151	3161	3154	3124	3185	3148.10

The T-test was used to find if there is a difference in mean between the $\mu_{Adj\ S}$ collected from the adjusted parameter level and the $\mu_{S\ (OP2\text{-}Shrinkage)}$ collected from the optimized parameter level for Shrinkage. The hypothesis is defined as:

$$H_0: \mu_{S\ (OP2\text{-}Shrinkage)} = \mu_{Adj\ S}$$
$$H_1: \mu_{S\ (OP2\text{-}Shrinkage} \neq \mu_{Adj\ S}$$

where $\mu_{S\ (OP2\text{-}Shrinkage)}$ is the mean of the μ_S collected from running experiments using the optimized shrinkage parameter level settings, and $\mu_{Adj\ S}$ is the mean of the μ_S collected from running experiments using the adjusted parameter level settings.

The T-test is analyzed with a t-value of 2.75 which falls inside of t-critical value (with alpha = 0.01 degree of freedom = 10) which equals 2.76. Thus, we fail to reject the null hypothesis. In conclusion, this result means that the adjusted parameters have an effect on the shrinkage. After the shrinkage, another T-test was used to find if there is a difference in mean between the $\mu_{Adj\ T}$ collected from the adjusted parameter level and the $\mu_{T\ (OP\text{-}Tensile\ strength))}$ collected from the optimized parameter level from Tensile strength. The hypothesis is defined as:

$$H_0: \mu_{T\ (OP\text{-}Tensile\ strength)} = \mu_{Adj\ T}$$
$$H_1: \mu_{T\ (OP\text{-}Tensile\ strength)} \neq \mu_{Adj\ T}$$

where $\mu_{T\ (OP\text{-}Tensile\ strength)}$ is the mean of the μ_T collected from running experiments using the optimized tensile parameter level settings, and $\mu_{Adj\ T}$ is the mean of the μ_T collected from running experiments using the adjusted parameter level settings. Table XI shows the $\mu_{Adj\ T}$ collected from the adjusted parameter level and the $\mu_{T\ (OP\text{-}Tensile\ strength)}$ collected from the optimized parameter level for Tensile strength.

The t-value is 2.28 which falls inside of t-critical value (with alpha = 0.01 degree of freedom = 10) which equals 2.76. Thus, we fail to reject the null hypothesis. In conclusion, this result means that the adjusted parameters have an effect on the Tensile strength.

After adjusting the optimal parameters we failed to reject the null hypothesis for both shrinkage and tensile strength in the T-test. With failing to reject both the null hypothesis, one single optimized parameter level setting can be used for improving both output variables at the same time.

VII. SUMMARY AND CONCLUSION

From the baseline study, the average of the output variables shrinkage and tensile strength are found to be 0.00217% error and 2904.8 Psi. After using the Taguchi design and collecting the data from L16, Individual optimized parameter level settings are found. But the optimal parameter settings for both the Shrinkage and Tensile strength are not same. We got two optimal parameters for the shrinkage and one optimized parameter setting for tensile strength. Separate confirmation runs are made for shrinkage, and the final optimized setting is chosen which is smaller. The optimized parameter run for the shrinkage has an average of 0.0002%. And optimized parameter run for the tensile strength has an average of 3204.7 psi. Once the data were analyzed from the adjusted parameter level settings, the shrinkage value was found to be 0.0031% and the tensile strength value was found to be 3148.1 psi. Although the adjusted parameter level settings did not yield better results compared to optimum parameters individually, both output variables are improved using the adjusted parameters with the following characteristics:

- Tensile strength is improved from 2908.4 psi to 3148 psi.
- Shrinkage error is reduced from 2.17% to 0.31%.
- Shot volume has shown more effect on the shrinkage than any other control variable.
- Mold temperature and injection speed have shown an utmost effect in the QC.
- Mold temperature and injection speed have shown very good effect on the tensile strength of the material.

The results demonstrate that Taguchi methodology, through the systematic optimization of machine parameters, enables the production of injection molded products with less shrinkage and higher tensile strength. Further studies could use this methodology in studying different QC like warpage, flash, sink marks and furthermore improvement of tensile and shrinkage by considering more or different control factors.

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