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The Effect of Cooling Time and Colorant Pigment on the Dimensional Accuracy of Plastic Injection Molded Closure

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Abstract

Dimensional accuracy is a critical aspect of precision injection molding, with the products generally required to conform to set tolerances. Major causes of these deviations are reported to be related to the polymer material, part geometry, injection mold design, and process parameters. This study investigated the effects of material color pigment and its interaction with process cooling time on product dimensional accuracy. This study was conducted experimentally, where three levels of cooling time and four material color pigment types were used to design a complete factorial experiment. The injection molding process used a 32-cavity injection mold to form closures at parameter combinations. The lateral and transverse dimensions of the samples produced from each experiment were measured, and averages were computed. Mains effect and interaction effect plots were made to determine the impact of process parameters on dimensional variation. Closures made from blue colorants had the lowest dimensional error, whereas white paint had the most significant dimensional error. The lower dimensional error was obtained for all the colors at more down-cooling times. The relationship between colorant and dimensional deviation depends on the cooling time for both dimensions. Cooling time (48%) and paint (37%) significantly affected the dimensional stability of the internal diameter. In contrast, only colorant (83%) and cooling time (48%) significantly affected the dimensional stability of the closure height and external diameter, respectively. To obtain zero-dimensional error, a black pigment could be used with a process cooling time of 1.8s, while a blue pigment material could be used with a cooling time of 2.6s. The result of this study provides insight into process cooling time optimization for dimensional error control at different material pigment colors.

Keywords: Injection molding, dimensional accuracy, cooling time, color pigments

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INTRODUCTION

Quality control is an essential aspect of plastic injection molding, and the formation of a product of a precise size and shape in tight tolerance applications has been a significant concern for engineers and researchers. Studies involving the investigation and optimization of major dimension-related defects such as dimensional instability have been the central theme of many injection molding-related research. Various studies have targeted optimizing major process parameters affecting product dimensional accuracy [1]. Literature reports that the dimensional accuracy of injection molded parts largely depends on the polymer material composition [2], process parameters [3], part geometry design, and injection mold design, among others.

A study by Mani et al. [4] investigated the effects of three process parameters such as melt temperature, injection velocity, and injection pressure, on the dimensional accuracy of a micro-injection molded part and inferred that higher values of melt temperature and injection pressure resulted in higher dimensional accuracy. Also, Masato et al. [5] studied the effects of process parameters and fiber orientation on the dimensional accuracy of injection molded parts. Furthermore, Kuo et al. [6] studied the impact of four major process parameters on the dimensional accuracy of an injection-molded product. The study yielded packing pressure as the most significant parameter of the four. A numerical study by He et al. [7] on the effect of process parameters on dimensional deviation yielded melt temperature as the most significant parameter.

Although significant strides have been made in terms of investigation of the effects of process parameters on product dimensional accuracy, there is limited information in the literature regarding the impact of the introduction of particular parameters, such as material colorant pigments and their interactions with significant process parameters in affecting product dimensional accuracy. Colorants are an integral part of injection-molded consumer and industrial products and are mainly used for identification, visual impression, and brand recognition. As such, this study seeks to determine the relationship between material pigment color and cooling time on product dimensional accuracy. This study will provide insights to injection molding entities on optimization of cooling time at various colorant pigments to control product dimensional error.

METHOD

Previous operational records indicated cooling time as the most significant factor affecting the closure's dimensional variation. The other process parameters were held constant to explicitly carry out a study on the effect of cooling and color pigment on dimensional variation. A complete factorial design of the experiment was developed, encompassing three levels of cooling time, that is, 1.6s, 2.6s, and 3.6s, and four types of material color pigments, namely black, blue, white, and colorless, yielding a 12-run array.

Injection molding experiments were carried out on a CX MC6 series injection molding machine with a 32-cavity hot runner mold. Each run yielded 32 closure samples whose internal diameters, external diameters, and heights were measured using a digital caliper and average dimensions computed.

Deviations in dimensions were computed concerning the desired dimensions of 26.6 mm for internal diameter, 28.6 mm for external diameter, and 38.10 mm for closure height. Percentage error in deviation was expressed as a percentage deviation from the desired dimensions.

Mains effect and interaction effect plots were made to determine the individual results of the parameters on dimensional variation and the optimum values of cooling time at each colorant computed. An ANOVA was carried out to determine the significance of the two parameters' influence on dimensional error.

This study was carried out experimentally with the study design illustrated on Figure 1.

RESULTS AND DISCUSSIONS

Table 1 presents a summary of results obtained from the experiments showing variations in internal diameter (Di), external diameter (Do) and height (H) of closures with varying colorants and cooling time. The means, mean deviations and percentage errors in internal and external diameters obtained are close indicating a uniform deviations among the two dimensions. Black colorant at 1.6 seconds and blue colorant at 3.6 seconds resulted to negative deviations in all dimensions.

Mains Effects

Figure 2 illustrates the main effect of colorant and cooling time on internal diameter dimensional variation. The plot shows that blue colorant closures (BE) had the lowest mean inner diameter, whereas white (WT) closures had the highest mean internal diameter. Similarly, blue colorant closures yielded the lowest deviation from the required diameter, while white ones yielded the highest variation from the required diameter dimension. For all the colorants, lower mean internal diameters were obtained at lower cooling time levels, and higher mean diameters were obtained at higher cooling time levels. An increase in cooling time increased the mean internal diameters and deviations from the required dimensions. This is because higher cooling times result in higher residual stress levels, which induces more dimensional variations in the part; therefore, a reduction in cooling time would lower dimensional variation. The results agree with those of Kamber [8], who also reported increased dimensional deviation with increasing cooling time. Similarly, a numerical study by He et al. [7] proposed a shorter-time high-speed cooling technology to reduce dimensional variation.

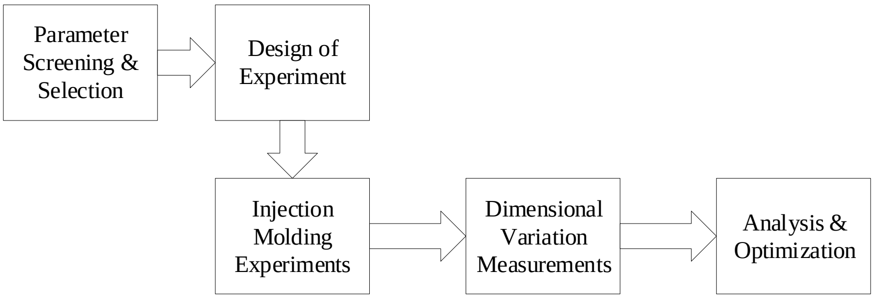

Figure 1. Study design.

Table 1. Summary of experimental results.

Run	Colorant	Cool Time	Means of Responses			Mean Deviations			Percentage Error		
			Di	***Do***	***H***	***Di***	***Do***	***H***	***Di***	***Do***	***H***
1	Black	1.6	26.58	28.58	38.09	-0.02	-0.02	-0.01	-0.08	-0.07	-0.03
2	Black	2.6	26.68	28.68	38.09	0.08	0.08	-0.01	0.30	0.28	-0.03
3	Black	3.6	26.79	28.78	38.10	0.19	0.18	0.00	0.71	0.63	0.00
4	Blue	1.6	26.34	28.33	38.02	-0.26	-0.27	-0.08	-0.98	-0.94	-0.21
5	Blue	2.6	26.63	28.63	38.06	0.03	0.03	-0.04	0.11	0.10	-0.10
6	Blue	3.6	26.81	28.82	38.06	0.21	0.22	-0.04	0.79	0.77	-0.10
7	White	1.6	26.72	28.72	38.09	0.12	0.12	-0.01	0.45	0.42	-0.03
8	White	2.6	26.85	28.85	38.10	0.25	0.25	0.00	0.94	0.87	0.00
9	White	3.6	26.95	28.95	38.10	0.35	0.35	0.00	1.32	1.22	0.00
10	Colorless	1.6	26.69	28.69	38.10	0.09	0.09	0.00	0.34	0.31	0.00
11	Colorless	2.6	26.78	28.78	38.10	0.18	0.18	0.00	0.68	0.63	0.00
12	Colorless	3.6	26.78	28.78	38.10	0.18	0.18	0.00	0.68	0.63	0.00

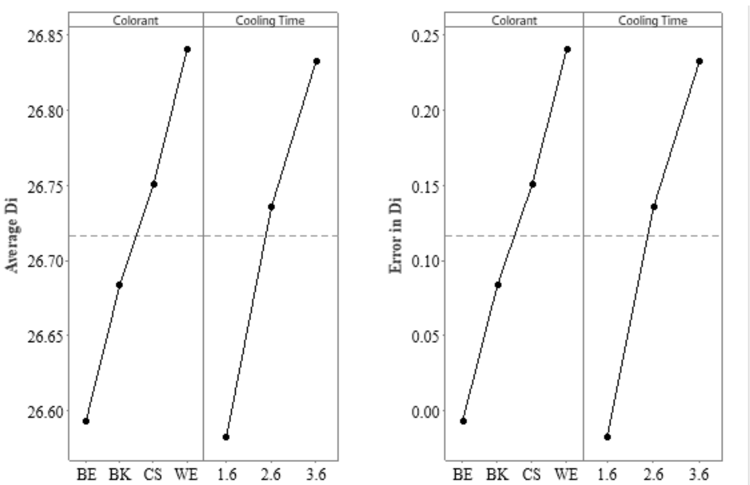

Figure 2. Mains effect plot showing average values and deviations in internal diameter dimensions.

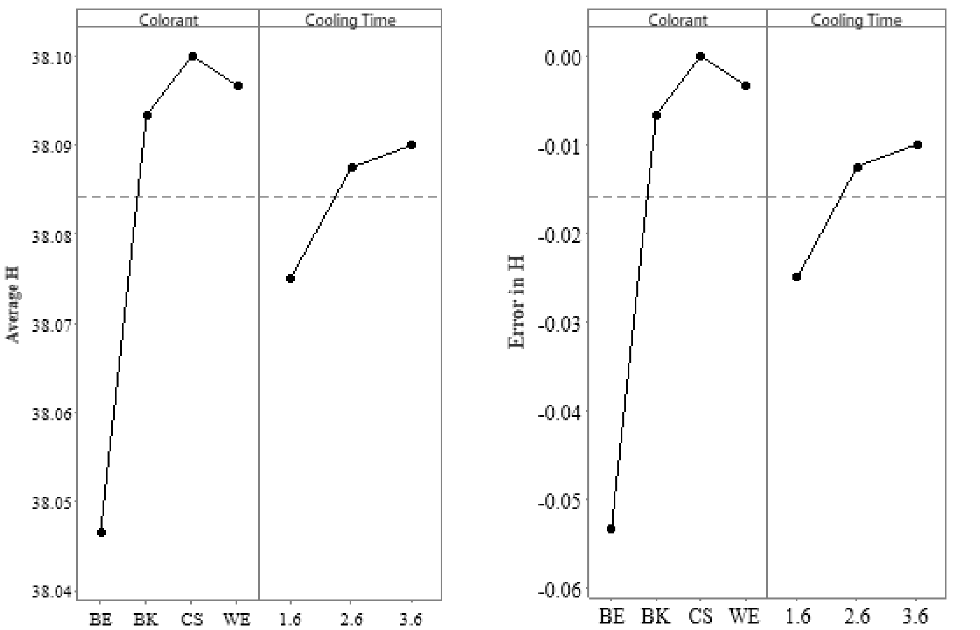

Figure 3. Mains effect plot showing average values and deviations in closure height dimensions.

Similar relationship was observed in external diameter responses for the average dimensions and deviations from required dimensions.

A mains effect plot of average dimensions and average deviations from the required closure height dimension is given in Figure 3. Closures with blue colorants recorded the lowest average height and average variations from the required size. In contrast, those without colors recorded the highest average height and average deviations from the required height. Like external and internal diameter responses, lower average measurements were obtained at more down cooling times, while higher values were obtained at higher cooling times. However, the degree of the effect of cooling time on closure height dimension was lower than that of internal and external diameter dimensions.

The main effect plots indicate that closures with darker colorants (black and blue) had lower dimensional deviations than closures with lighter colorings (white and colorless) for all the measured dimensions. Upon ejection, due to lower heat dissipation, there was a slow cooling rate for closures with lighter colors, which induced more residual stresses, resulting in higher dimensional variation compared to darker colors. Also, the dimensional deviations were more pronounced along transverse dimensions (diameters) than lateral dimensions (height).

Interaction Effects

Figure 4 illustrates an interaction plot between colorant and cooling time and the effect on the dimensional deviation of the closure internal diameter and height. The interaction plots are not parallel, indicating that the relationship between colorant and dimensional deviation depends on the cooling time for both dimensions. This is because the closure dimensional variation is a function of both in and post-mold cooling rates. In-mold cooling depends on the set cooling time, while post-mold cooling depends on the speed of heat transfer from the closure surface to the environment, which is affected by the material color. For all colorants, the dimensional deviation could be higher or lower depending on the level of cooling time. This deviation was higher at 3.6s and lower at 1.6s cooling time. A blue colorant closure processed at 3.6s would have more significant dimensional variations than a white colorant closure processed at 1.6s cooling time.

The interaction between colorant and cooling time and its effect on internal diameter variation is illustrated by a contour plot on Figure 5. To achieve lower deviations in internal diameter, a black closure should be cooled between 1.6 and 2.6 s whereas a blue closure should be cooled at 2.6s. The other lighter color closures should be cooled at lower cooling times.

Figure 6 plots the percentage error in internal diameter deviations and depicts how close each colorant is to a desired percentage error of zero within the cooling time interval of 1.6 to 3.6. These plots were found to match those of external diameter closely. Blue and black colorant plots cross the target, while white and colorless stories lie well above the target line and do not closely approach the target within the cooling interval of 1.6 to 3.6s. By linear approximation, closures with black colorants would have zero variation in internal diameter at a cooling time of 1.8 seconds, while closures with blue coloring would have zero internal diameter variation at 2.63 seconds. However, since the cooling time cannot be reduced beyond 1.6 seconds, achieving a zero deviation in internal and external diameters for white and colorless closures may not be possible.

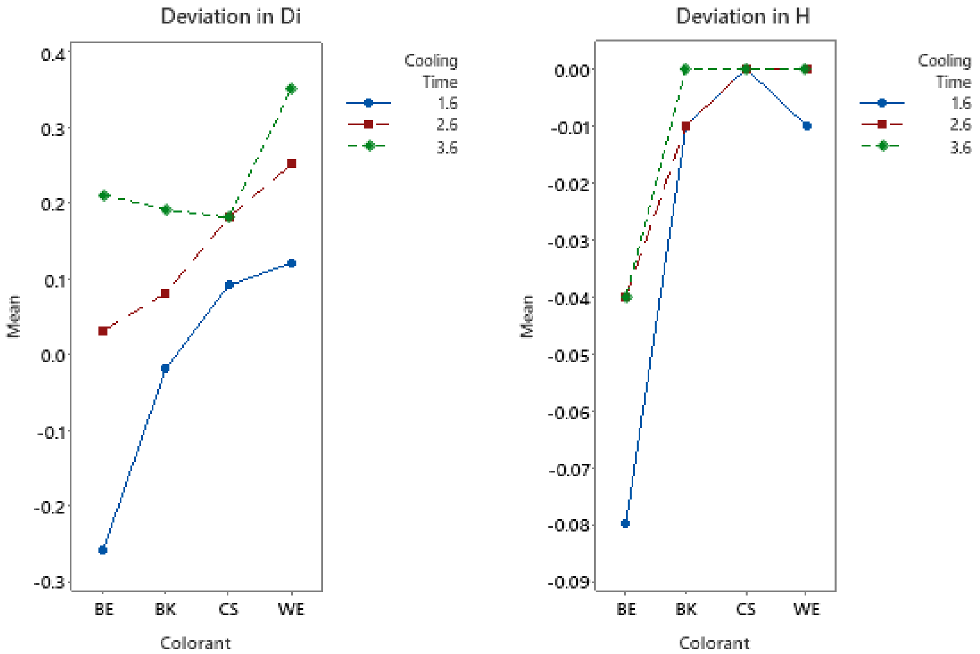

Figure 4. Colorant and cooling time interaction plots for internal diameter and height.

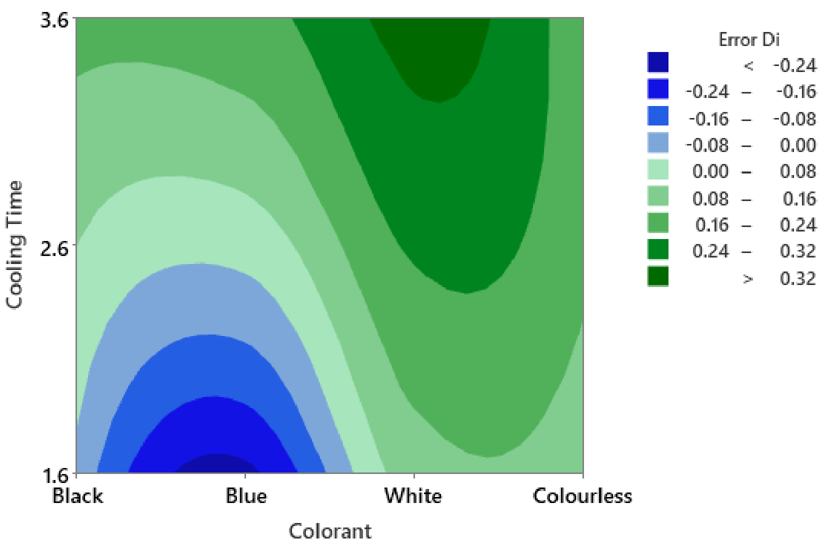

Figure 5. Contour plot illustrating interaction between colorant and cooling time for internal diameter variation.

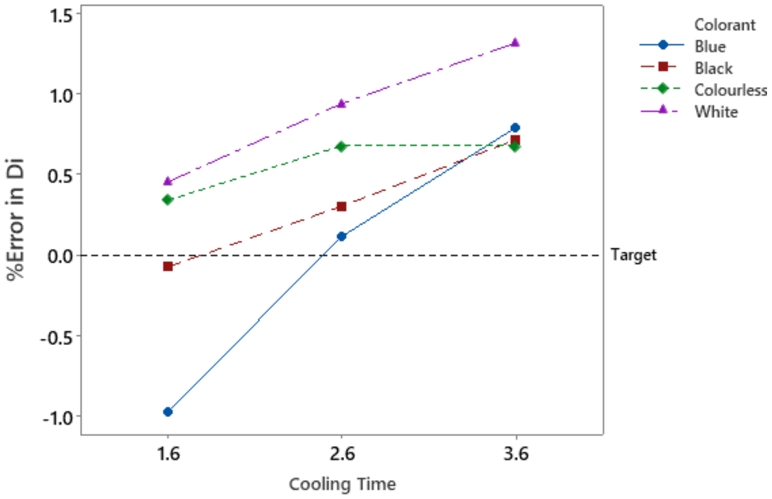

Figure 6. Percentage error in internal diameter deviations.

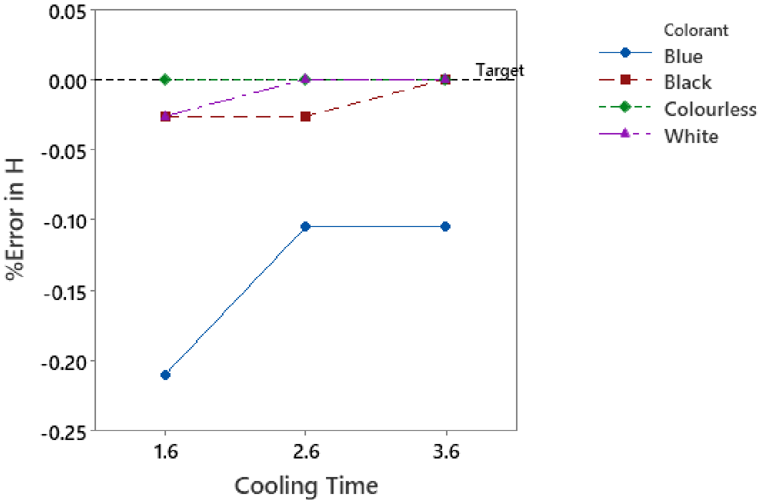

Figure 7. Percentage error in height deviations.

However, for the closure height, colorless closures had a zero percentage deviation in height for all the cooling time levels while closures with white and black colorant had zero percentage deviation at two and one levels of cooling times respectively as illustrated on Figure 7.

ANOVA

Table 2 shows the ANOVA results of dimensional errors in internal diameter (a), external diameter (b), and closure height (c) calculated at alpha = 0.05. For inner diameter, both cooling time and colorant significantly contributed to dimensional variation, with cooling time having the most significant contribution of 48%. However, for external diameter, only the cooling time ($p = 0.02$) substantially affected dimensional error with a donation of 47%. In contrast, only the colorant ($p = 0.003$) significantly affected dimensional error for the closure height, with a contribution of 83%. These differences in the significance of process parameters in affecting dimensional variations among internal and external diameters were also obtained by Baruffi et al. [9].

These results imply that colorant and cooling time significantly contribute to the dimensional variation and, hence, dimensional inaccuracy in the injection molded closures. Controlling this variation requires using a specific coloring at one particular cooling time. Since material colorant selection depends on customer preference, optimizing the cooling times for each colorant would help reduce or eliminate dimensional inaccuracy in the products.

Table 2. ANOVA for dimensional variations

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Di							
Colorant	3	0.09793	37.03%	0.09793	0.032644	4.96	0.046
Cooling Time	2	0.12702	48.03%	0.12702	0.063508	9.64	0.013
Error	6	0.03952	14.94%	0.03952	0.006586		
Total	11	0.26447	100.00%				
Do							
Colorant	3	0.09863	36.17%	0.09863	0.032875	4.45	0.057
Cooling Time	2	0.12972	47.57%	0.12972	0.064858	8.77	0.017
Error	6	0.04435	16.26%	0.04435	0.007392		
Total	11	0.27269	100.00%				
H							
Colorant	3	0.005692	82.59%	0.005692	0.001897	16.66	0.003
Cooling Time	2	0.000517	7.50%	0.000517	0.000258	2.27	0.185
Error	6	0.000683	9.92%	0.000683	0.000114		
Total	11	0.006892	100.00%				

CONCLUSION

This study aimed to determine the effects of cooling time and colorant on the dimensional accuracy of injection molded closures. The study obtained the main interaction and ANOVA effects through experimental investigation, which yielded significant factors affecting dimensional accuracy. The following conclusions were made from this study;

- Variations in cooling time and colorant affect the dimensional accuracy of the internal diameter, external diameter, and closure height in varying degrees.
- Darker colors like black and blue have higher dimensional accuracies, while lighter colors like white and colorless have lower dimensional accuracies.
- In all colorants, an increase in cooling time increases the product's dimensional inaccuracy
- The effect of material colorant on product dimensional accuracy depends on the process cooling time.
- Cooling time and colorant significantly affect the dimensional accuracy of the internal diameter. In contrast, only paint and cooling time significantly affect the dimensional accuracy of the closure height and external diameter, respectively.
- Optimization of the process cooling time for each material colorant could control product dimensional accuracy.

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