Experimental Study of Mechanical Properties of PC/PMMA Blends by Injection Molding Process

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Abstract - Mechanical engineering is one of the quite important properties of plastics articles. Most of pure plastics materials are rarely found to have both strength and high toughness. The purpose of this study is to investigate the optimization of mechanical properties for the maximum tensile strength, elongation, and impact strength of Polycarbonate and Polymethyl methacrylate (PC/PMMA) blends by means of injection molding process. PC/PMMA plastics composites with different concentrations are first blended by plastic mixer. Tensile and impact specimens designed according to ASTM, type V are injection molded by injection molding machine. Taguchi's method is then used to find the optimal parameters for the maximum tensile strength, elongation and impact strength. The tensile and impact testing show that process conditions, including composition, melt temperature, packing pressure, and cooling time are considered mentioned in this study. An ANOVA table has been achieved for determining the significance of injection molding parameters. Results of experiments show that the composition is found as the most significant parameter for improvement of mechanical properties of PC-PMMA plastics composites. Toughness of PC/PMMA plastics composites increases with the increase of PC content in PMMA. In contrast, higher tensile strength results from the decrease in PC concentration. Packing pressure and melt temperature have been found as the second and third most significant parameters on tensile strength, respectively. However, cooling time is considered as the second most significant parameter to toughness and melt temperature secondly contribute to tensile elongation. It is necessary to simultaneously consider three mechanical properties in plastics composites, thus verification parameters suitable for tensile strength, elongation, and impact strength were defined. After experimental verification, the mechanical properties of the PC/PMMA plastics composites have been improved significantly. In particular, average ultimate tensile strength is 76.47 MPa, average elongation is 17.47mm, and impact strength is 7429.53 J/m^2.

Keywords- Polycarbonate, PMMA, polymer blend, tensile strength, impact strength, toughness.

I. INTRODUCTION

Polycarbonate (PC) and Polymethyl methacrylates (PMMA) blends have been studied with several sample preparation methods, such as film casting in different solutions (THF, CH_2Cl_2), methanol and heptane precipitation from THF solution, and melt blending [1]. In general, PMMA exhibits advantageous properties, including transparency with transmittance of 92%, high surface hardness, good weatherability, chemical resistance, and ultraviolet resistance. However, it can be seen that their limitations are low impact strength, low temperature stability, and poor dimensional stability.

For PC materials, there are numerous useful properties as high impact strength, high heat capability, good dimensional stability, as well as optical clarity with transmittance of 83%. Nevertheless, disadvantageous properties appearing in PC material include poor scratch resistance, stress birefringence, and poor ultraviolet resistance. Blending of PC with PMMA would therefore be expected to achieve improved mechanical and optical properties for a wide range of applications.

Previous studies that show the miscibility, mechanical compatibility of PC/PMMA blends are dependent on mixing conditions, such as compositions, mixing temperature, mixing speed, mixing time, and even catalysts added to the blends [2]. Tjong et al. [3] studied tensile deformation mechanisms of the PC/PMMA blends prepared by screw extrusion thanks to the dilatometric measurements. Tensile specimens (ASTM D638-91, type I) were made by injection molding process. PC/PMMA 50/50 blend exhibits the tensile behavior of ductile polymer composites that indicate the highest engineering stress in comparison with other concentrations. In addition, they used the quantitative model of Heikens et al [4] to present the contribution on longitudinal strain of elastic, shear, and crazing deformation mechanisms. The results show that with pure PMMA and the PC/PMMA 10/90 blend, appearance of crazing considered as plastic deformation is much more, but pure polycarbonate and the PC/PMMA 90/10 blend show to be dominant of shear deformation. Nevertheless, the ratio of PC/PMMA 50/50 blend is the best composition suitable for total elongation contribution. Jan Rybnicek et al. [5] produced the binary and ternary blends from three materials such as PC, ABS, and PMMA. Melt blending was employed to make the blends from original and recycled materials in broad range of compositions. The toughness of PC/PMMA blend decreases with the increase of PMMA contents. Nanostructure of PMMA/PC blends fabricated by high-shear processing technique not only improves much more transparency of polymer composites, but also exhibits higher modulus than pure PC or vice versa [6].

Treatment conditions including temperature, time affect tensile properties of as-blended samples made of PC/PMMA 70/30 blend by solution casting and annealing in a hot press. The as-blended samples without heat treatment show the highest tensile strength and the largest strain at break. In contrast, the results that indicate deterioration of tensile behaviors are with highly treatable temperature and/or long treatable time [7]. Dynamic Mechanical Analyser (DMA) was employed to analyze mechanical properties of PC/PMMA blends prepared by solution casting method in five different concentrations. Stress-Strain scan represents that the increase in composition of PC up to 50% leads to Young's modulus, ultimate strength, and tensile strength increased. These mechanical properties are decreased as the compositions of PC exceed than 50% [8]. Elongation at break and fracture energy of the PC/PMMA blends made by solution casting method increase with the increasing in composition of PC in PMMA polymer by Dynamic Mechanical Analyser (DMA) [9].

Those studies above have improved the mechanical properties of the PC/PMMA blends that were generally performed by two manners. First, the PC/PMMA blends prepared by solution casting method were analyzed of mechanical properties through Dynamic Mechanical Analyser. Other methods use tensile and impact testing machine to measure strength of specimens. The mechanical properties are then completely calculated and characterized based on the stress-strain curves as well as applied load and extension in length of the specimens. It can be clearly seen that these researchers only focused on effects of mixing conditions containing the most significant influence of the compositions of the PC/PMMA blends and the treatment conditions after sample preparation on the mechanical properties. The objective of this study is to investigate injection molding parameters affecting tensile and impact strength of the blends of PMMA and PC using injection molding machine and tensile/impact testing machine.

II. *EXPERIMENTAL SET-UP AND METHODS*

A. *Materials and blending*

The materials used in this study are PMMA (Acryrex CM-205) obtained from Chi Mei Co, Ltd., Taiwan with weight average molecular weight (M_w) of around 81,000g/mol and PC (Panlite L-1225L) supplied by Teijin Chemical Ltd. with weight average molecular weight says 35,400g/mol. Before mixing, the PMMA and PC pellets are dried in a vacuum oven at 85^0C and 120^0C for 24 h, respectively.

According to previous researches [4, 9, 10], which show that the composition in weight of PC/PMMA blend was 50/50 percentage being suitable for miscibility, compatibility, and few mechanical behaviors. In this paper, therefore, the researchers used the compositions of PC/PMMA blends, including 20/80, 50/50, and 80/20 weight fraction for experiment. The blends are prepared by compounding the dried pellets of the PMMA and PC in Plastic mixer JCW2.

B. *Injection molding machine and sample preparation*

The experimental set-up of an electrical injection machine (FANUC Roboshot α15iA) with the maximum injection pressure 240MPa and injection velocity 200mm/s equipped with diameter 16mm injection screw. Experimental mold was made of the mold steel H13. Mold temperature controller is used with water as a coolant during the injection molding process. Tensile and impact specimens according to ASTM D638, type V were fabricated by this machine.

C. *Mechanical testing*

Tensile measurements were performed at room temperature (23^0C) using INSTRON tensile testing machine (model 3365). Speed of testing corresponding to crosshead position was 5mm/min. (~0.2in./min.). Applied loads and extensions indicated by testing screen were employed to calculate tensile strength, elongation and construct stress-strain curves. With regard to impact testing, impact tester utilized to measure impact strength was Basic Pendulum Impact (BPI) Tester.

D. *Design of Experiment*

The control parameters selected in this study are composition of PC (A), melt temperature (B), packing pressure (C), and cooling time (D). Table 1 shows the control factors and levels of Taguchi experiments.

In order to evaluate the effect of the injection molding parameters to the mechanical properties of the PC/PMMA plastics composites, an L_9 orthogonal array [10] of three levels with 4 parameters, shown as table 2, was used for experimental design. Nine treatments were performed and each one was repeated three times.

The quality characteristics of the mechanical properties are tensile strength, elongation, and impact strength. The signal-to-noise (S/N) ratio is usually used to justify the effects of parameters. In this investigation, the maximum tensile strength, elongation, and impact strength are desired. Therefore, the quality characteristics for tensile strength, elongation, and impact strength is Larger-the-better (LTB) expressed as the equation 1.

$$\eta_{LTB} = -10log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right]. \quad (1)$$

Where η_{LTB} is the signal-to-noise ratio for LTB, y_i is the experimental value of i^{th} part (ultimate tensile strength, elongation or impact strength) and n is the total number of experimental parts (n=3). According to the Taguchi's technique, a larger signal-to-noise value indicates better quality characteristic. Therefore, the objective of this experiment is to maximize the signal-to-noise value(η_{LTB}). It means that desired values are maximum tensile strength, elongation, and impact strength.

TABLE 1 THE CONTROL FACTORS AND LEVELS OF TAGUCHI EXPERIMENTS

Factors	Levels		
	1(-1)	2(0)	3(+1)
Composition of PC, A (%)	20	50	80
Melt temperature, B (^{0}C)	235	255	275
Packing pressure, C (MPa)	35	55	75
Cooling time, D (s)	20	25	30

TABLE 2: DESIGN TABLE L_9 OF EXPERIMENTAL METHOD

Test No.	A	B	C	D
	Composition of PC	Melt temperature	Packing pressure	Cooling time
1	20	235	35	20
2	20	255	55	25
3	20	275	75	30
4	50	235	55	30
5	50	255	75	20
6	50	275	35	25
7	80	235	75	25
8	80	255	35	30
9	80	275	55	20

III. RESULTS AND DISCUSSION

A. Tensile strength

Table 3 shows the experimental results, average values, and S/N ratios of the tensile strength of 9 different experimental conditions. The results represent small deviations of average values and corresponding replications in the same injection molding parameters. The response is tensile strength in MPa. The values as table 4 are calculated by means of the mean value of all experiments that are the same level. The Delta (Δ) is defined as the equation (2). The value of delta (Δ) reflects the significance rank of each factor.

$$\text{Delta } (\Delta) = \max(S/N) - \min(S/N) \quad (2)$$

Figure 1 is the signal-to-noise ratio plot of experimental results for tensile testing. It is obvious that tensile strength decreases with the increase in PC composition. Melt temperature, packing pressure, and cooling time increasing from level 1 to level 2 lead to the increase in tensile strength. Optimal setting of parameters is $A_1B_2C_2D_2$, i.e., A = 20 % of PC composition, B = 255 ^{0}C, C = 55 MPa, D = 25 s. Table 5 is the results of the ANOVA analysis and the composition of PC is the most significant parameter with a confidence level of 95%.

TABLE 3: THE TAGUCHI L_9 ORTHOGONAL ARRAY WITH EXPERIMENTAL RESULTS FOR TENSILE TESTING

Tensile testing, unit: MPa					S/N ratio (dB)
No.	1	2	3	Average	η_{LTB}
1	76.1904	78.3321	75.2185	76.5803	37.6786
2	80.7614	79.3116	79.0888	79.7206	38.0303
3	75.058	75.6133	75.4600	75.3771	37.5447
4	71.6965	72.0674	73.5189	72.4276	37.1966
5	73.5389	73.5332	72.0618	73.0446	37.2706
6	74.1121	71.0838	73.1107	72.7689	37.2350
7	67.7572	67.4438	65.5785	66.9265	36.5092
8	66.4688	68.713	67.9915	67.7244	36.6124
9	68.2099	67.9805	69.1624	68.4509	36.7069

TABLE 4 RESPONSE TABLE FOR S/N RATIOS, LTB FOR TENSILE STRENGTH

Level	Comp.	Melt temperature	Packing pressure	Cooling time
1	37.7512	37.1281	37.1753	37.2187
2	37.2340	37.3044	37.3112	37.2582
3	36.6095	37.1622	37.1082	37.1179
Delta (Δ)	1.1417	0.1763	0.2031	0.1403
Rank	1	3	2	4

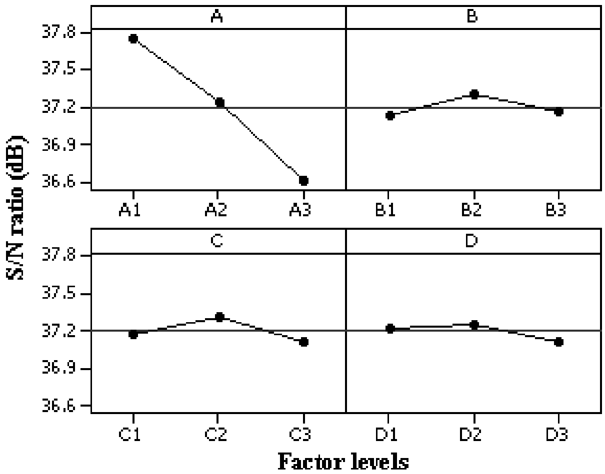

Fig. 1 S/N plot of experimental results for tensile strength

TABLE 5 ANOVA FOR SIGNIFICANT PARAMETERS OF TENSILE STRENGTH ($F_{2, 2, 0.05}$ = 19.0)

Source	SS	dof	MS	F	P
A. Comp. of PC	1.9610	2	0.9805	62.4522	0.0158
B. Melt temperature	0.0525	2	0.0262	1.6688	0.3747
C. Packing pressure	0.0642	2	0.0321	2.0446	0.3285
Error (pooled with D)	0.0314	2	0.0157		
Total	2.1091	8			

B. Tensile elongation

Similarly, table 6 shows the experimental results and S/N ratios of the tensile elongation in mm and response table for S/N ratio is shown as table 7. Figure 2 plots S/N of experimental results for tensile elongation. It can be easily seen that tensile elongation increases with the increase of PC composition. Packing pressure is slightly significant effect to elongation. The optimal combination of injection molding parameters is $A_3B_1C_2D_1$, namely, the PC composition of 80 %, melt temperature of 235^{0}C, packing pressure of 55 MPa, and cooling time of 20 s. Analysis of variances, as shown in table 8, exhibits the most significant parameter of composition of PC.

TABLE 6 THE TAGUCHI L_9 ORTHOGONAL ARRAY WITH EXPERIMENTAL RESULTS FOR TENSILE ELONGATION

Tensile elongation testing, unit: mm					S/N ratio (dB)
Test No.	1	2	3	Average	η_{LTB}
1	7.6622	9.6159	8.4823	8.5868	18.5650
2	8.4419	7.4708	3.0630	6.3252	13.3556
3	3.1331	2.6338	2.3616	2.7095	8.4839
4	15.3439	15.7156	16.6023	15.8873	24.0069
5	16.8364	12.5319	17.3972	15.5885	23.5657
6	10.1114	10.0136	10.1070	10.0773	20.0667
7	21.3073	21.4694	20.5776	21.1181	26.4886
8	14.7830	10.4394	15.5017	13.5747	22.2395
9	18.1675	18.3294	16.9387	17.8119	24.9978

TABLE 7 RESPONSE TABLE FOR S/N RATIOS, LTB FOR TENSILE ELONGATION

Level	Comp.	Melt temperature	Packing pressure	Cooling time
1	13.4682	23.0202	20.2904	22.3762
2	22.5464	19.7203	20.7868	19.9703
3	24.5753	17.8495	19.5128	18.2434
Delta (Δ)	11.1071	5.1707	1.2740	4.1328
Rank	1	2	4	3

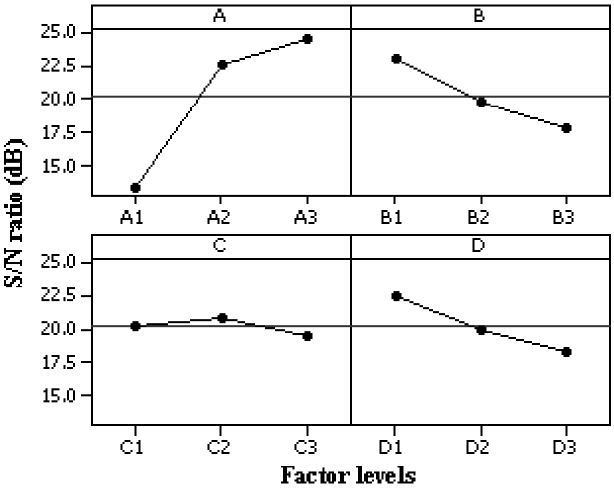

Fig. 2 S/N plot of experimental results for tensile elongation

TABLE 8 ANOVA FOR SIGNIFICANT PARAMETERS OF TENSILE ELONGATION ($F_{2,\,2,\,0.05}$ = 19.0)

Source	SS	dof	MS	F	P
A. Comp. of PC	209.900	2	104.950	84.842	0.0116
B. Melt temp.	41.125	2	20.563	16.623	0.0567
D. Cooling time	25.850	2	12.925	10.449	0.0873
Error (pooled with C)	2.474	2	1.237		
Total	279.349	8			

C. *Impact strength*

Table 9 shows L_9 orthogonal array with experimental results for impact strength in J/m^2. The impact strength values are much greater than pure PC material as PC concentration contains 50 % to 80%. Similar to the elongation, packing pressure is found to be small significance to impact value. The optimized combination of the factors for impact strength is $A_3B_1C_3D_2$, i.e., PC concentration of 80 %, melt temperature of 235 ^{0}C, packing pressure of 275 MPa, and cooling time of 25 s. ANOVA table, as shown in table 11, represents that PC content is the most significant process condition with the confidence level of 95 %.

TABLE 9 THE TAGUCHI L_9 ORTHOGONAL ARRAY WITH EXPERIMENTAL RESULTS FOR IMPACT STRENGTH

Test No.	Impact testing, unit: J/m^2 1	2	3	Average	S/N ratio(dB) η_{LTB}
1	3063.7255	4289.2157	3982.8431	3778.5948	71.2700
2	3676.4706	3982.8431	3063.7255	3574.3464	70.9051
3	3063.7255	3370.0980	2757.3529	3063.7255	69.6376
4	6127.4510	5821.0784	5514.7059	5821.0784	75.2760
5	5514.7059	5514.7059	6127.4510	5718.9542	75.1146
6	6433.8235	6740.1961	5514.7059	6229.5752	75.7921
7	8578.4314	8578.4314	8884.8039	8680.5556	78.7674
8	6127.4510	6127.4510	7046.5686	6433.8235	76.1138
9	6127.4510	7046.5686	7659.3137	6944.4444	76.7217

TABLE 10 RESPONSE TABLE FOR S/N RATIOS, LTB FOR IMPACT STRENGTH

Level	Comp.	Melt temperature	Packing pressure	Cooling time
1	70.6042	75.1045	74.3920	74.3688
2	75.3942	74.0445	74.3009	75.1549
3	77.2010	74.0504	74.5065	73.6758
Delta (Δ)	6.5967	1.0600	0.2056	1.4791
Rank	1	3	4	2

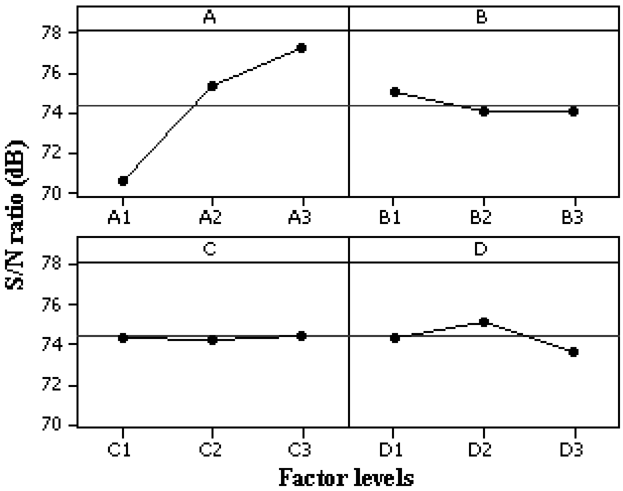

Fig. 3 S/N plot of experimental results for impact strength

TABLE 11 ANOVA FOR SIGNIFICANT PARAMETERS OF IMPACT STRENGTH ($F_{2,\,2,\,0.05}$ = 19.0)

Source	SS	dof	MS	F	P
A. Comp. of PC	69.7247	2	34.8623	1096.2987	0.0009
B. Melt temp.	2.2345	2	1.1173	35.1352	0.0277
D. Cooling time	3.2860	2	1.6430	51.6667	0.019
Error (pooled with C)	0.0637	2	0.0318		
Total	75.3089	8			

D. *Verification test of optimal parameters*

Table 12 presents the summary of optimal combinations for three responses, tensile strength, elongation, and impact strength. Due to the mechanical properties of the PC/PMMA plastics composites significantly depending on compositions of PC polymer, PC/PMMA plastics composites containing higher PC compositions lead to the plastics composites with lower tensile strength or vice versa. Based on experimental results, 20 % PC is better for enhancement of tensile strength, but elongation and impact strength are higher at PC composition of 80 %. Consequently, a PC composition of 50 % (A_2) was considered as appropriate concentration for experimental verification. In regard to the packing pressure, tensile strength and elongation have the same optimal level (C_2); the C_3 level contributes to higher impact strength but slightly increase, hence packing pressure of 55 MPa (C_2) was used for verification. Cooling times at D_2 (25 s) are the same effect to the maximum tensile and impact strength, thus the study is supposed to select the cooling time of 25 s (D_2) for confirmation experiment. The last parameter is the melt temperature. It is clear that lower melt temperature is suitable for increasing elongation and impact strength, but it causes the decrease in tensile strength. Therefore, an average value (B_0 = 245^{0}C) of the melt temperatures was dominant to choose for verification test. It can be concluded that the verification parameters are A_2 B_0 C_2 D_2, namely, PC composition of 50 %, melt temperature of 245 ^{0}C, packing pressure of 55 MPa, and cooling time of 25 s. After experiment with these verification parameters, experimental results show that mean ultimate tensile strength is 76.47 MPa, mean elongation is 17.47 mm, mean impact strength is 7429.53 J/m^2. It can be clearly seen that these values are much higher in comparison with the average tensile strength, elongation, and impact strength of PC/PMMA 50% before verification (average tensile strength = 72.75 MPa, mean elongation = 13.85 mm, and average impact strength = 5923.20 J/m^2). Figure 3 is illustration of stress-strain curves of PC/PMMA plastics composites after verification test.

TABLE 12 SUMMARY OF OPTIMAL COMBINATIONS FOR THREE RESPONSES and VERIFICATION PARAMETERS

Responses	Optimal combinations			
Tensile strength	A_1	B_2	C_2	D_2
Elongation	A_3	B_1	C_2	D_1
Impact strength	A_3	B_1	C_3	D_2
Verification parameter	A_2	B_0	C_2	D_2

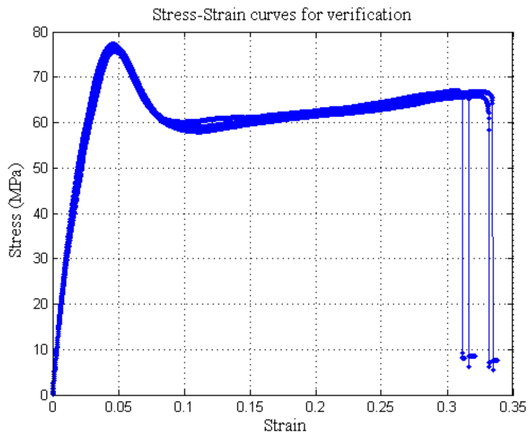

Fig. 3 Stress-Strain curves for verification test

Regression analysis is used to investigate and model the relationship between a response variable and one or more predictors, and to predict the trend of dependent variable as a function of independent variables. In this study, the control parameters are independent variables, and tensile strength, elongation, or impact strength are the dependent variables. The regression model is performed based on the results of regression analysis. Linear regression models achieved are:

Tensile strength = 83.3 – 4.76 composition + 0.11 melt temperature – 0.288 packing pressure – 0.424 cooling time

Elongation = 6.66 + 5.81 composition – 2.50 melt temperature + 1.20 packing pressure – 1.64 cooling time

Impact strength = 2417 + 1940 composition – 340 melt temperature + 170 packing time – 187 cooling time

IV. CONCLUSION

This study has investigated the effect of injection molding parameter to mechanical properties due to Taguchi L_9 orthogonal array. With the optimal parameters achieved from the experimental design, composition of PC is the most significant parameter for improvement of the mechanical behaviours. Higher PC content results in the lower tensile strength but larger impact strength and longer elongation. Generally speaking, packing pressure is responsible for tensile strength higher than the impact strength and elongation. The effect of cooling time to the impact and elongation response is quite larger than the tensile strength. The melt temperature has a lower similar influence degree on tensile and impact but high melt temperature degrading polymer composites causes low tensile and impact strength. The mean ultimate tensile strength, elongation and impact strength reached after verification are 76.47 MPa, 17.47 mm, 7429.53 J/m^2, respectively.

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