Injection Molding Study on the Strength of Weld Line for Polycarbonate and Carbon Fiber Composite Material

Chen-Yuan Chung¹, Chin-Chang Yeh², Chia-Min Lin¹

¹Department of Mechanical Engineering, National Central University, Taoyuan City, Taiwan
²Department of Mechanical Engineering, Oriental Institute of Technology, New Taipei City, Taiwan

*E-mail: cxc474@case.edu

Abstract. In this study the polycarbonate (PC) and carbon fiber (CF) are used as the experimental materials to investigate the impact of injection molding process parameters on tensile strength of weld line using Taguchi method and response surface methodology. The experiments are conducted via 27 sets of parameter combinations designed based on carbon fiber content, melt temperature, mold temperature, injection speed, injection pressure, packing speed, and packing pressure. The process parameter combination with the highest tensile strength is identified using Taguchi method. Later on, the response surface methodology is used to establish the tensile strength predicting formula formed by process parameters in order to understand the correlation between process parameters and tensile strength. The experimental and analysis results indicate the melt temperature and mold temperature have the most significant impacts on tensile strength.

1. Introduction

During the injection molding process, the forming of weld line is generated by the merging of two flow fronts of plastic melts. In the molecular bonding region, the directions of molecular chains of melts are in parallel with each other, thus reducing the molecular bonding in the weld region and resulting in poorer mechanical property [1] in the weld region. Therefore, there are many scholars hoping to predict the structural strength of weld line via derivation of formula. The theoretical molecular chain self-diffusion model proposed by Kim and Suh [2] in 1986 has been wildly applied to the calculation of prediction of mechanical strength and birefringence of weld line. In addition to the analysis of weld-line strength via theoretical model, there were also many scholars investigating the impacts of manufacturing processes on weld-line strength. Chen et al [3] investigated the impacts of different parameters, such as melt temperature, mold temperature, injection speed, and packing pressure, on weld-line strength of ABS material. It was found that weld-line specimens molded at higher melt temperature, higher mold temperature, faster injection speed, and lower packing pressure would lead to better mechanical properties. In recent years, U.S. Department of Energy has been applying the manufacturing of long-carbon-fiber reinforced thermoplastic composites to lightweight materials [4]. Yan and Cao [5] investigated the structure and interfacial shear strength of glass fiber/carbon fiber reinforced polypropylene hybrid composites fabricated by the direct fiber feeding injection molding process. The process could improve the fiber lengths and orientation distributions and thus increasing the shear strength.
This study presents an experimental approach followed by rigorous statistical techniques to identify the optimal combination of process parameters that can maximize the weld-line strength of PC composite reinforced with CF. The Taguchi method and response surface methodology are used to investigate the impacts of injection molding process parameters on the weld-line strength of CF/PC composite. Additionally, the tensile strength of weld line is verified by the experiments conducted based on optimal injection molding parameters. The weld line is vulnerable to failure due to reduced mechanical strength. It is expected that the manufacturing process optimization of this paper can serve as the reference for quality improvement of plastic product.

2. Materials and Methods

2.1. Experimental equipment
The pure PC and CF/PC used in this study are produced by Kotec Corporation (Osaka, Japan). First the hopper dryer is used for four hours of dehumidifying at the high temperature of 120°C, and then the injection molding machine (SM150HCV, Asian Plastic Machinery Co., Ltd.) is used in coordination with mold temperature controller (TOD-200, Wedlon Automation Co. Ltd.) to produce test specimen. Finally, the tensile tests were performed on a universal testing machine (AI-7000M, Gotech Testing Machines Inc.) at a crosshead speed of 5 mm/min according to ASTM D638 (Type I) standard. Furthermore, analysis of experimental data was performed based on Taguchi method and response surface methodology using Minitab software (Minitab Inc., State College, PA, USA).

2.2. Taguchi method
The Taguchi method was applied to determine the effects of process parameters on the weld-line strength and the optimal set of parameters that would maximize the weld-line strength. An L^27(3^7) orthogonal array was selected for the experimental design for each of the seven factors. The three levels for the seven parameters were identified during the 27 experiments (Table 1). In order to maximize the weld-line strength, the formula of S/N ratio describing the larger-the-better characteristic was based on the following equation.

\[ S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \]  

where \( y_i \) is the measured property for the \( i \)th tensile test, \( n \) is the number of tests. The analysis of variance (ANOVA) was performed using Minitab to obtain the effects of the process parameters on mechanical property. In this way, optimal levels of the process parameters can be estimated.

2.3. Response surface methodology
Different from the Taguchi method, response surface methodology basically combines statistical and experimental methods with data-fitting techniques. Based on the response acquired in the experiments, regression analysis is utilized to identify the relationships between the response and the design variables. The mathematical relationship of the \( Y \) response on the corresponding parameters is usually expressed by the following second-order polynomial equation [6, 7]:

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \epsilon \]  

where \( Y \) is the observed response (mechanical property), \( k \) is the number of design variables, \( \beta_0 \) is a constant. \( \beta_i, \beta_{ii}, \beta_{ij} \) are the linear, quadratic and interaction coefficients, respectively. \( x_i \) and \( x_j \) are the design variables that correspond to the injection process parameters. \( \epsilon \) is the random error.
Table 1. Orthogonal array $L_{27}(3^7)$ of the experimental runs for Taguchi method.

| run | Factor A Carbon fiber (%) | Factor B Melt temperature (°C) | Factor C Mold temperature (°C) | Factor D Injection pressure (bar) | Factor E Packing pressure (bar) | Factor F Injection speed (mm/s) | Factor G Packing speed (mm/s) |
|-----|-------------------------|-------------------------------|-------------------------------|---------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 1   | 0                       | 270                           | 50                            | 50                              | 10                            | 20                            | 20                            |
| 2   | 0                       | 270                           | 50                            | 50                              | 30                            | 30                            | 30                            |
| 3   | 0                       | 270                           | 50                            | 50                              | 50                            | 40                            | 40                            |
| 4   | 0                       | 290                           | 70                            | 70                              | 10                            | 20                            | 20                            |
| 5   | 0                       | 290                           | 70                            | 70                              | 30                            | 30                            | 30                            |
| 6   | 0                       | 290                           | 70                            | 70                              | 50                            | 40                            | 40                            |
| 7   | 0                       | 310                           | 90                            | 90                              | 10                            | 20                            | 20                            |
| 8   | 0                       | 310                           | 90                            | 90                              | 30                            | 30                            | 30                            |
| 9   | 0                       | 310                           | 90                            | 90                              | 50                            | 40                            | 40                            |
| 10  | 5                       | 270                           | 70                            | 90                              | 10                            | 30                            | 40                            |
| 11  | 5                       | 270                           | 70                            | 90                              | 30                            | 40                            | 20                            |
| 12  | 5                       | 270                           | 70                            | 90                              | 50                            | 20                            | 30                            |
| 13  | 5                       | 290                           | 90                            | 50                              | 10                            | 30                            | 40                            |
| 14  | 5                       | 290                           | 90                            | 50                              | 30                            | 40                            | 20                            |
| 15  | 5                       | 290                           | 90                            | 50                              | 50                            | 20                            | 30                            |
| 16  | 5                       | 310                           | 50                            | 70                              | 10                            | 30                            | 40                            |
| 17  | 5                       | 310                           | 50                            | 70                              | 30                            | 40                            | 20                            |
| 18  | 5                       | 310                           | 50                            | 70                              | 50                            | 20                            | 30                            |
| 19  | 10                      | 270                           | 90                            | 70                              | 10                            | 40                            | 30                            |
| 20  | 10                      | 270                           | 90                            | 70                              | 30                            | 20                            | 40                            |
| 21  | 10                      | 270                           | 90                            | 70                              | 50                            | 30                            | 20                            |
| 22  | 10                      | 290                           | 50                            | 90                              | 10                            | 40                            | 30                            |
| 23  | 10                      | 290                           | 50                            | 90                              | 30                            | 20                            | 40                            |
| 24  | 10                      | 290                           | 50                            | 90                              | 50                            | 30                            | 20                            |
| 25  | 10                      | 310                           | 70                            | 50                              | 10                            | 40                            | 30                            |
| 26  | 10                      | 310                           | 70                            | 50                              | 30                            | 20                            | 40                            |
| 27  | 10                      | 310                           | 70                            | 50                              | 50                            | 30                            | 20                            |

3. Results and Discussions
The tensile specimen of injection molding is fabricated according to the regulation of ASTM-D638 TYPE I, and the injection molding experiment is conducted according to $L_{27}(3^7)$ orthogonal array. Five
samples are molded under each set of molding conditions, and such sample is the tensile specimen fabricated according to the ASTM-D638 Standard (Figure 1).

![Figure 1. Geometry and dimension of tensile test specimen.](image)

At the beginning the Taguchi method is used, and the L\textsuperscript{27} (3\textsuperscript{7}) orthogonal array is used to arrange different process parameters for investigating the tensile strength of test specimen (Table 2), and then the optimal process parameter combinations can be obtained via the S/N response graphs of tensile strength against various factors (Figure 2) in order to enhance the mechanical property of finished product. The factor response graph (Figure 2) reveals that the best tensile strength process parameter combination of weld-line specimen is “A3-B3-C2-D1-E1-F2-G1”. The analysis of variance (ANOVA) is used to evaluate the experimental error and significance test of factor. The ranking of influences of various process parameters on tensile strength is as shown in Table 3. In the end, the experiment is conducted via the optimal process parameter combination obtained by Taguchi method, “A3-B3-C2-D1-E1-F2-G1”, and it is proven that the tensile strength is as high as 82MPa (Figure 3).

![Figure 2. The effect of each factor on tensile strength of weld line.](image)
### Table 2. Mechanical properties of the tested specimens.

| run | Sample 1  | Sample 2  | Sample 3  | Sample 4  | Sample 5  | Average  | Standard deviation | S/N ratio |
|-----|-----------|-----------|-----------|-----------|-----------|----------|--------------------|-----------|
| 1   | 56.22     | 56.88     | 54.55     | 55.98     | 55.66     | 55.858   | 0.857              | 34.939    |
| 2   | 55.63     | 56.18     | 55.84     | 55.60     | 54.59     | 55.568   | 0.594              | 34.895    |
| 3   | 55.71     | 56.33     | 56.49     | 56.58     | 56.38     | 56.298   | 0.343              | 35.009    |
| 4   | 60.72     | 60.68     | 60.43     | 60.49     | 61.2150   | 60.706   | 0.307              | 35.664    |
| 5   | 60.86     | 61.68     | 61.35     | 61.86     | 61.40     | 61.430   | 0.381              | 35.767    |
| 6   | 60.22     | 61.02     | 61.79     | 61.02     | 61.61     | 61.132   | 0.616              | 35.724    |
| 7   | 60.05     | 61.29     | 60.86     | 60.15     | 59.11     | 60.292   | 0.836              | 35.603    |
| 8   | 61.65     | 62.40     | 62.23     | 61.48     | 62.15     | 61.982   | 0.396              | 35.845    |
| 9   | 61.87     | 61.00     | 62.67     | 62.91     | 61.98     | 62.086   | 0.751              | 35.858    |
| 10  | 62.81     | 61.59     | 60.18     | 62.06     | 61.96     | 61.720   | 0.968              | 35.806    |
| 11  | 59.73     | 56.89     | 55.15     | 55.19     | 55.86     | 56.564   | 1.905              | 35.039    |
| 12  | 56.26     | 51.65     | 53.87     | 53.29     | 52.88     | 53.590   | 1.700              | 34.571    |
| 13  | 56.60     | 58.92     | 57.48     | 57.96     | 56.66     | 57.524   | 0.967              | 35.194    |
| 14  | 59.20     | 59.97     | 59.02     | 59.83     | 59.88     | 59.580   | 0.437              | 35.501    |
| 15  | 58.70     | 59.28     | 58.28     | 59.83     | 58.38     | 58.894   | 0.653              | 35.400    |
| 16  | 60.54     | 58.21     | 60.08     | 59.60     | 58.57     | 59.400   | 0.988              | 35.473    |
| 17  | 62.07     | 59.01     | 60.84     | 60.53     | 61.08     | 60.706   | 1.110              | 35.661    |
| 18  | 61.05     | 60.48     | 62.67     | 61.39     | 60.57     | 61.232   | 0.885              | 35.737    |
| 19  | 48.54     | 42.69     | 43.21     | 41.28     | 41.87     | 43.518   | 2.904              | 32.731    |
| 20  | 41.84     | 42.71     | 40.40     | 42.01     | 41.33     | 41.658   | 0.859              | 32.389    |
| 21  | 43.41     | 42.91     | 42.41     | 43.57     | 43.58     | 43.176   | 0.508              | 32.702    |
| 22  | 65.81     | 73.73     | 73.56     | 72.03     | 71.95     | 71.416   | 3.242              | 37.053    |
| 23  | 71.90     | 71.45     | 69.56     | 69.47     | 70.93     | 70.662   | 1.102              | 36.981    |
| 24  | 71.89     | 76.25     | 77.10     | 76.23     | 78.33     | 75.960   | 2.431              | 37.601    |
| 25  | 80.62     | 81.95     | 81.89     | 81.33     | 81.91     | 81.540   | 0.574              | 38.227    |
| 26  | 70.65     | 77.83     | 77.84     | 76.56     | 76.71     | 75.918   | 3.006              | 37.589    |
| 27  | 72.05     | 77.03     | 78.02     | 79.33     | 78.10     | 76.906   | 2.835              | 37.704    |
Table 3. Summary of ANOVA results for the weld-line strength.

| Factor | Sum of squares | DOF | Variance | F value | Confidence | Rank |
|--------|----------------|-----|----------|---------|------------|------|
| A      | 6.5663         | 2   | 3.2832   | 1.48473 | 76.9%      | 4    |
| B      | 124.9790       | 2   | 62.4895  | 28.25930| 100.0%     | 1    |
| C      | 69.5459        | 2   | 34.7729  | 15.72518| 100.0%     | 2    |
| D      | 58.4092        | 2   | 29.2046  | 13.20705| 100.0%     | 3    |
| E      | 0.2957         | 2   | 0.1479   | 0.06687 | 6.5%       | 6    |
| F      | 1.5218         | 2   | 0.7609   | 0.34411 | 29.0%      | 5    |
| G      | 0.0427         | 2   | 0.0213   | 0.00965 | 1.0%       | 7    |
| Error  | 288.8194       | 108 | 2.2113   | 8= 1.4870|            |      |
| Total  | 1272.5178      | 134 |          |         |            |      |

Figure 3. Tensile strength test of specimen made using Taguchi optimized parameters.

The Rank in Table 3 indicates that factor B (melt temperature) and factor C (mold temperature) are the important factors affecting the tensile strength of weld line. Therefore, other factors are fixed at the combination of A3-D1-E1-F2-G1, and the factors of B and C are adopted as the input variables. And then Minitab is used to plot the response surface as shown in Figure 4.
Figure 4. Response surface and contour plot of the tensile strength as a function of the melt temperature and the mold temperature.

The statistic software Minitab is used to establish the response surface method, and the tensile strength equation of non-interactive predicted under second-order model is:

\[
Tensile \ strength = -1020 - 0.777A + 7.34B + 2.178C - 3.247D - 0.117E + 0.601F + 0.055G + 0.1282A^2
- 0.01203B^2 - 0.01711C^2 + 0.02312D^2 + 0.00182E^2 - 0.00871F^2 - 0.00122G^2
\]  

(3)

The search of optimal solution of tensile strength equation will lead to the optimal combination of process parameters (Figure 5) of tensile strength, which includes CF 10%, melt temperature of 305.55°C, mold temperature of 64.54 °C, injection pressure of 50 bar, packing pressure of 10 bar, injection speed of 40 mm/s, and packing speed of 20 mm/s. The result of response surface method is approaching to the result of Taguchi method, while the results of these two analyses of factor F (injection speed) are different. However, the significance of factor F is lower, so it can be neglected. The comparison between the experimental results based on Taguchi method and response surface method is as shown in Table 4, where there is a certain difference between the analysis results of factor B (melt temperature) and factor C (mold temperature). So it is speculated that Taguchi method can only be used to search for the local optimum at the levels, while the response surface methodology can be used to find the global optimum outside the levels.

Figure 5. Optimized process parameters for maximum strength of weld line.
Table 4. Comparison of the optimized process parameters predicted using Taguchi method with that predicted by response surface method.

| Factor            | Taguchi method | Response surface method |
|-------------------|----------------|-------------------------|
| A – Carbon fiber (%) | 10             | 10                      |
| B – Melt temperature (°C) | 310            | 305.55                  |
| C – Mold temperature (°C) | 70             | 64.54                   |
| D – Injection pressure (bar) | 50             | 50                      |
| E – Packing pressure (bar) | 10             | 10                      |
| F – Injection speed (mm/s) | 30             | 40                      |
| G – Packing speed (mm/s) | 20             | 20                      |

4. Conclusions
In this study Taguchi method is adopted to find the optimal process parameters in order to enhance the tensile strength of finished product, and then ANOVA is used to evaluate the errors in the experiment to enhance the credibility of experimental result. And then the response surface method is used for fine tuning of important process parameters, and it is verified that the optimal process parameters are obtained by Taguchi method. This study reveals that the factors affecting weld-line strength of polycarbonate are in the order of melt temperature, mold temperature, injection pressure, fiber content, injection speed, packing pressure, and packing speed. The tensile strength of weld line will be increased along with the increase of melt temperature. This is because that the increase of melt temperature will reduce the material viscosity, and there will be sufficient time for molecular entanglement to result in enhanced bonding rate. The result of this experiment can serve as the process improvement method to enhance the mechanical strength of plastic product, and it can be used to replace the metal to achieve the goal of weight reduction.

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6. References
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