# Single Performance Optimization of Micro Metal Injection Molding for the Highest Green Strength by Using Taguchi Method

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**Abstract**

Micro metal injection molding is drawing attention recently as one the most cost effective processes in powder metallurgy to produce small-scale intricate part and competitive cost for mass production of micro components where it is greatly influenced by injection parameter. Thus, this paper investigated the optimization of highest green strength which plays an important characteristic in determining the successful of micro MIM. Stainless steel SS 316L was used with composite binder, which consists of PEG and PMMA while SA works as a surfactant. Feedstock with 61.5% with several injection parameters were optimized which highly significant through screening experiment such as injection pressure(A), injection temperature(B), mold temperature(C), injection time(D) and holding time(E). Besides that, interaction effects between injection pressure, injection temperature and mold temperature were also considered to optimize in the Taguchi's orthogonal array. Analysis of variance (ANOVA) in terms of signal-to-noise ratio (S/N-larger is better) for green strength was also presented in this paper. Result shows that interaction between injection temperature and mold temperature (BxC) give highest significant factor followed by interaction between injection pressure and injection temperature (AxB). Single factor that also contributes to significant optimization are mold temperature(C), injection time (D) and injection pressure (A). Overall, this study shows that Taguchi method would be among the best method to solve the problem with minimum number of trials.

Keywords**:** analysis of variance, micro metal injection molding, Taguchi's orthogonal array, S/N ratio

# 1. INTRODUCTION

Micro metal injection molding are gaining better potential where currently most of the researchers using this method in producing small scale intricate part with better production cost. During the injection molding process, some of the green part has to be identified in terms of density, strength, defect, etc. If molding process parameters can be adjusted in an intelligent way, the characteristics that needed might be maximize or minimize towards an acceptable way. Some traditional approach does not produce satisfactory results in a wide range of experimental settings as it vary only one factor while others keep fixed. Optimization methods alone or integrated with other methods provide very effective techniques in finding the best process parameters values leading to least warpage, shrinkage, distortion and other defect[1-4].

Nowadays, optimization of the process parameter are gaining much interests among researchers as it can minimize defects, cost and obtain high efficiency in the planning or experiments. Design of Experiment (DOE) technique brings some researchers to identify the quality parameter need to be control for example Ji et al[5] measure the effects of sintering factors on the properties of the sintered parts. Khairur et al[6] has been using classical Design of Experiment technique to study the effects of injection parameters on the green part quality characteristics such as green density, green strength and green defects. Other researchers that using Taguchi as a medium tool to optimize their parameter including Ghani et al[7], Ahmad et al[8], Chen et al[9],Tuncay et al[10] and Oktem et al[11]. This is because from another experiments in another area of study such as plastic molding, metal removal processes, the Taguchi method is recognized as a systematic application of design and analysis of experiments for the purpose of designing and improving product quality. Taguchi's method is statistically a robust technique and has proven to be reliable [12] where high quality products can be produced in a short period of time and at better cost efficiency.

In this paper, optimization parameter to achieve highest green strength will be investigated using design of experiment (DOE) at which injection molding parameter are optimized using $L_{27}$ $(3^{13})$ Taguchi orthogonal array. The injection parameters that will be used are injection pressure, injection temperature, mold temperature, injection time and holding time. Furthermore, interactions between injection pressure, injection temperature and mold temperature will also be investigated. Powder loading will not included in the parameter as 61.5% would be the best based from research done by Ibrahim et al[13,14] using critical powder volume percentage(CPVP) and rheological characteristics. Continuity from this, analysis of variance (ANOVA) will take place to find the significant parameter that contributes to highest green strength. Confirmation test will be done in order to verify within the range of optimum performance calculation.

# 2. METHODOLOGY

## 2.1 Material

For the replication of fine details, fine particles powder around 5 µm are mixed with a multi-component binder consist of water soluble binder PEG and PMMA. The main objective of using PMMA binder is that it can be removed from the mouldings in a comparatively short time [16]. Stearic acid will act as a surfactant and lubricant to the feedstock for improving powder wetting. Table 2 show properties of the binder used in the study. A 316L stainless steel water atomised powder (Epson Atmix Corp) with irregular shape was used as it is compatible with water leaching and high corrosion resistance. Figure 1 show the SEM image of SS 316L(PF-10F). The characteristic of used powder are reported in Table 1 while Table 2 shows the chemical composition of the metal powder [13,14]. For micro injection molding tensile test, there's no MPIF standard will be using as it's not been established yet. In this research, the mold dimension will be as figure 1 while figure 2 shows the green part [15]:-

Table 1: Stainless steel (SS316L) powder characteristic

| Characteristic | Details |
|---|---|
| Identification | SS 316L, PF-10F |
| Powder Source | Epson Atmix Corp |
| Tap Density,g/cm$^3$ | 4.06 |
| True pynometer density,g/cm$^3$ | 8.0471 |
| Powder Size | $D_{10}$=2.87µm<br>$D_{50}$=5.96µm<br>$D_{90}$=10.65µm |

Table 2: Binder properties

| Binder | Type | Designation | Composition % | Melting temperature, °C | Density, gcm$^{-3}$ |
|---|---|---|---|---|---|
| Binder 1 | Primary | Polymethyl Methacrilate(PMMA) | 25 | 257.77 | 1.19 |
| Binder 2 | Secondary | Polyethelena Glycol(PEG) | 73 | 63.32 | 1.23 |
| Binder 3 | Surfactant | Stearic acid(SA) | 2 | 70.1 | 0.94 |

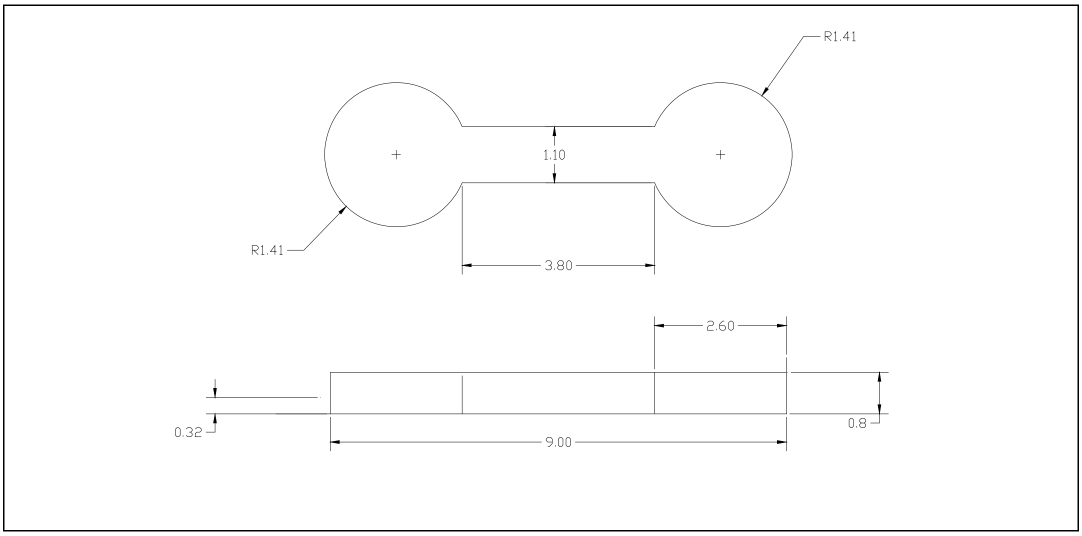


Figure 1: Micro mold dimension in mm

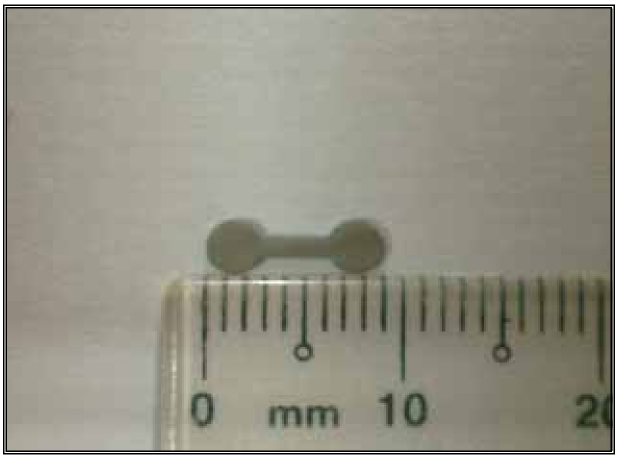


Figure 2: Green Part

## 2.1 Design of Experiment

For the optimization process, Taguchi's orthogonal array (statistical method) will be used in order to improve the green strength and the quality of the sample. In this case, the selection of experimental design is the backbone step in the procedure. Three-level designs of experiment with 5 parameters are consider in the injection molding where basically all of them are quite significant through screening test by using classical analysis of variance(ANOVA). The parameters that involved in the design are injection pressure, injection temperature, mold temperature, injection time and holding time as shown in table 3 below. With total 24 DOF for both single and interactions parameter, $L_{27}$'s Taguchi orthogonal array (3 level OA) is the most suitable for design of experiment. $L_{27}$ means that 27 runs will be conducted with 5 replications at each run in order to guarantee statistical accuracy. Table 4 show Taguchi's orthogonal array which demonstrates quality characteristic and allocation level of each parameter.

Table 3: Injection parameters for three level taguchi designs

| Level | Injection Pressure (bar) | Injection Temperature (°C) | Mold Temperature (°C) | Injection Time (s) | Holding Time (s) |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 0 | 10 | 150 | 55 | 5 | 5 |
| 1 | 11 | 155 | 60 | 6 | 6 |
| 2 | 12 | 160 | 65 | 7 | 7 |

## 3. RESULTS AND DISCUSSION

As mention before, Taguchi's orthogonal array will give much reduced variance for the experiment with optimum settings of control parameters. Thus the marriage of Design of Experiments (DOE) with optimization of control parameters to obtain best results is achieved in the Taguchi Method. "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results. Two of the applications in which the concept of SN ratio is useful are the improvement of quality via variability reduction and the improvement of measurement based on repetitive data. The SN ratio transforms several repetitions into one value which reflects the amount of variation present and the mean response. In this work, the characteristics needed are "larger the better" in order to optimize the green strength:-

$$S/N = -10 \log \left( \frac{1}{N} \sum_{j=1}^{n} \frac{1}{Y_{ij}^2} \right) \quad (1)$$

Where n is the total number of replication and $Y_{ij}$ is the value of green strength in MPa. The values are recorded in table 4 using Taguchi's orthogonal array.

Table 4: Taguchi's $L_{27}(3^{13})$ orthogonal array demonstrates the value of experimental trials(density) and quality characteristic

| Trial | Parameter | | | | | | | | | | | | | S/N RATIO : HIGHEST THE BETTER | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | | | | | | |
| | A | B | A X B | A X B | C | A X C | A X C | B X C | D | e | B X C | e | E | REP 1 | REP 2 | REP 3 | REP 4 | REP 5 | S/N(dB) |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13.50 | 13.06 | 13.11 | 13.43 | 13.05 | 22.42841 |
| 2 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 13.84 | 13.84 | 13.54 | 13.84 | 13.51 | 22.74162 |
| 3 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 13.89 | 13.42 | 13.43 | 13.43 | 13.67 | 22.64789 |
| 4 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 12.98 | 13.56 | 12.94 | 13.59 | 13.41 | 22.46854 |
| 5 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 0 | 0 | 0 | 14.84 | 14.16 | 13.24 | 14.15 | 13.52 | 22.89071 |
| 6 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 0 | 0 | 0 | 1 | 1 | 1 | 14.56 | 14.21 | 13.92 | 13.89 | 14.13 | 23.00646 |
| 7 | 0 | 2 | 2 | 2 | 0 | 0 | 0 | 2 | 2 | 2 | 1 | 1 | 1 | 13.46 | 13.40 | 13.55 | 13.57 | 13.49 | 22.60254 |
| 8 | 0 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 2 | 2 | 2 | 13.06 | 13.28 | 13.54 | 13.84 | 13.85 | 22.60877 |
| 9 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 14.16 | 14.14 | 15.60 | 14.06 | 14.09 | 23.15268 |
| 10 | 1 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 14.03 | 13.74 | 13.47 | 13.43 | 13.22 | 22.65123 |
| 11 | 1 | 0 | 1 | 2 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 13.94 | 14.21 | 14.24 | 14.51 | 14.34 | 23.07284 |
| 12 | 1 | 0 | 1 | 2 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 14.54 | 14.67 | 14.38 | 14.37 | 14.46 | 23.217 |
| 13 | 1 | 1 | 2 | 0 | 0 | 1 | 2 | 1 | 2 | 0 | 2 | 0 | 1 | 13.46 | 13.79 | 13.83 | 13.84 | 13.84 | 22.76579 |
| 14 | 1 | 1 | 2 | 0 | 1 | 2 | 0 | 2 | 0 | 1 | 0 | 1 | 2 | 14.55 | 14.53 | 14.26 | 14.12 | 13.94 | 23.09101 |
| 15 | 1 | 1 | 2 | 0 | 2 | 0 | 1 | 0 | 1 | 2 | 1 | 2 | 0 | 14.16 | 14.31 | 14.23 | 14.26 | 14.43 | 23.09283 |
| 16 | 1 | 2 | 0 | 1 | 0 | 1 | 2 | 2 | 0 | 1 | 1 | 2 | 0 | 14.16 | 14.09 | 14.06 | 13.94 | 14.27 | 22.98606 |
| 17 | 1 | 2 | 0 | 1 | 1 | 2 | 0 | 0 | 1 | 2 | 2 | 0 | 1 | 13.09 | 13.02 | 13.12 | 13.09 | 13.07 | 22.33074 |
| 18 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 1 | 2 | 0 | 0 | 1 | 2 | 13.51 | 13.21 | 13.88 | 13.00 | 13.97 | 22.60568 |
| 19 | 2 | 0 | 2 | 1 | 0 | 2 | 1 | 0 | 2 | 1 | 0 | 2 | 1 | 13.06 | 13.09 | 13.21 | 13.27 | 13.33 | 22.40541 |
| 20 | 2 | 0 | 2 | 1 | 1 | 0 | 2 | 1 | 0 | 2 | 1 | 0 | 2 | 13.84 | 14.44 | 14.57 | 14.28 | 14.01 | 23.05818 |
| 21 | 2 | 0 | 2 | 1 | 2 | 1 | 0 | 2 | 1 | 0 | 2 | 1 | 0 | 13.13 | 13.30 | 13.06 | 13.28 | 13.21 | 22.40823 |
| 22 | 2 | 1 | 0 | 2 | 0 | 2 | 1 | 1 | 0 | 2 | 2 | 1 | 0 | 13.24 | 13.80 | 13.24 | 13.51 | 13.19 | 22.53569 |
| 23 | 2 | 1 | 0 | 2 | 1 | 0 | 2 | 2 | 1 | 0 | 0 | 2 | 1 | 13.04 | 13.27 | 13.78 | 13.68 | 13.78 | 22.60653 |
| 24 | 2 | 1 | 0 | 2 | 2 | 1 | 0 | 0 | 2 | 1 | 1 | 0 | 2 | 13.11 | 13.21 | 13.11 | 13.27 | 13.47 | 22.43252 |
| 25 | 2 | 2 | 1 | 0 | 0 | 2 | 1 | 2 | 1 | 0 | 1 | 0 | 2 | 13.75 | 13.76 | 13.68 | 13.68 | 13.46 | 22.712 |
| 26 | 2 | 2 | 1 | 0 | 1 | 0 | 2 | 0 | 2 | 1 | 2 | 1 | 0 | 13.45 | 13.51 | 13.29 | 13.79 | 13.87 | 22.65597 |
| 27 | 2 | 2 | 1 | 0 | 2 | 1 | 0 | 1 | 0 | 2 | 0 | 2 | 1 | 13.51 | 14.15 | 14.63 | 14.87 | 14.36 | 23.09497 |
| | | | | | | | | | | | | | | | | | | $\Sigma$ | 614.27 |
| | | | | | | | | | | | | | | | | | | $\bar{T}$ | 22.7508 |

Figure 3 shows the main effects plot(data means) for the S/N ratio where the optimum parameter will be based on the highest peak at each parameter A,B,C,D and E. From the figure, the optimum configuration without considering interaction would be $A_1$ $B_1$ $C_2$ $D_0$ and $E_0$. In other words, it brings to injection pressure 11bar, injection temperature 155°C; mold temperature 65°C; injection time 5s; and holding time 5s. The main effects plot is developed from Table 1 above by using the mean of S/N ratio. For example, the optimum parameter for A is at level 1, so the mean S/N value will be calculated from total trial 10 to 18 and then divided by the number of trials as shown below:-

$$= \frac{22.65123 + 23.07284 + 23.217 + 22.67579 + 23.09101 + 23.09283 + 22.98606 + 22.33074 + 22.60568}{9}$$

$= 22.8661$ dB

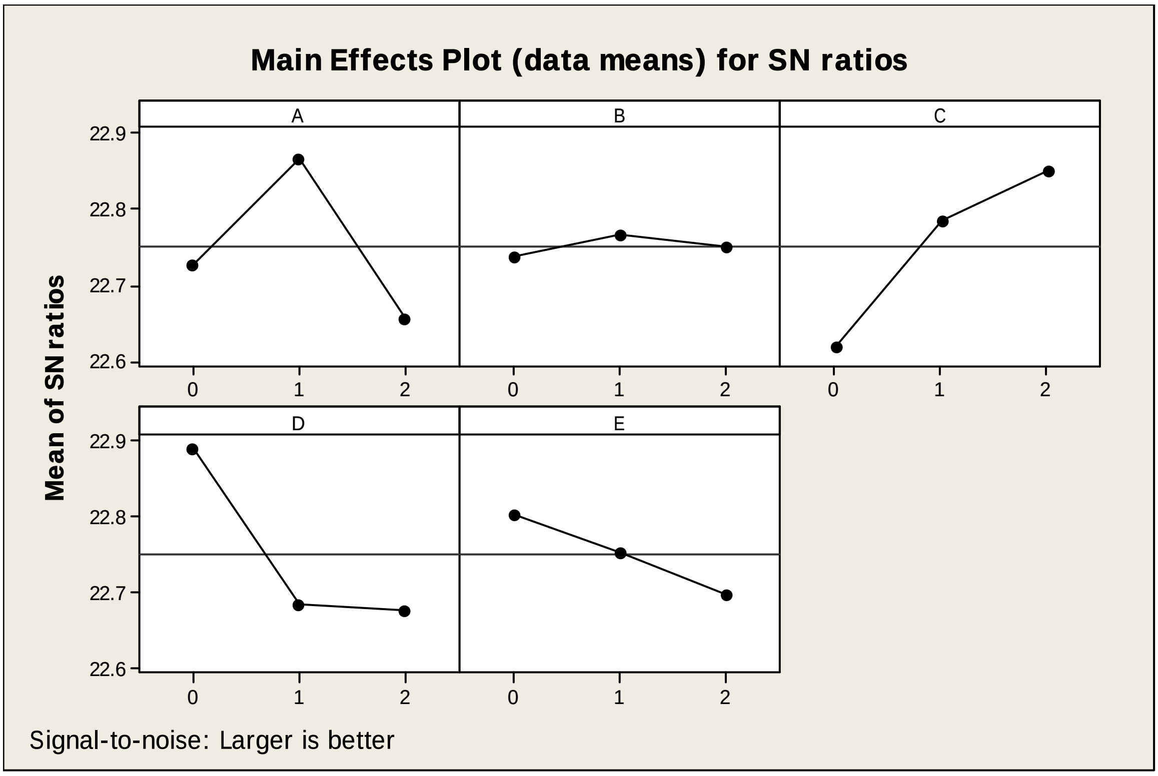


Figure 3: Main effects plot (data means) for S/N ratio

However in figure 4, after taking consideration on the interaction between AxB, AxC and BxC, the optimum configuration has changed or maintained depending on the highest S/N ratio. The S/N ratio of each interaction shown below is come from Figure 4 where it clearly shows that $A_1B_1$ and $A_1C_2$ were the highest mean S/N ratio. Thus after considering the interactions of factors A, B and C, the optimum configuration becomes $A_1$ $B_1$ $C_2$ $D_0$ and $E_0$. The optimum configuration hasn't changed even with interaction. It happens because these parameters were very significant and gives higher percentage of contribution through analysis of variance (ANOVA). In order to produce strong green part, combination between moderate injection pressure and injection temperature are the best criteria. The same goes to Jamaludin et al[6] where the finding shown that combination with high injection pressure and high injection temperature may cause binder to separate from the powder binder matrix. As a result, green part contains less binder to hold the powder particles and finally produce brittle green part.

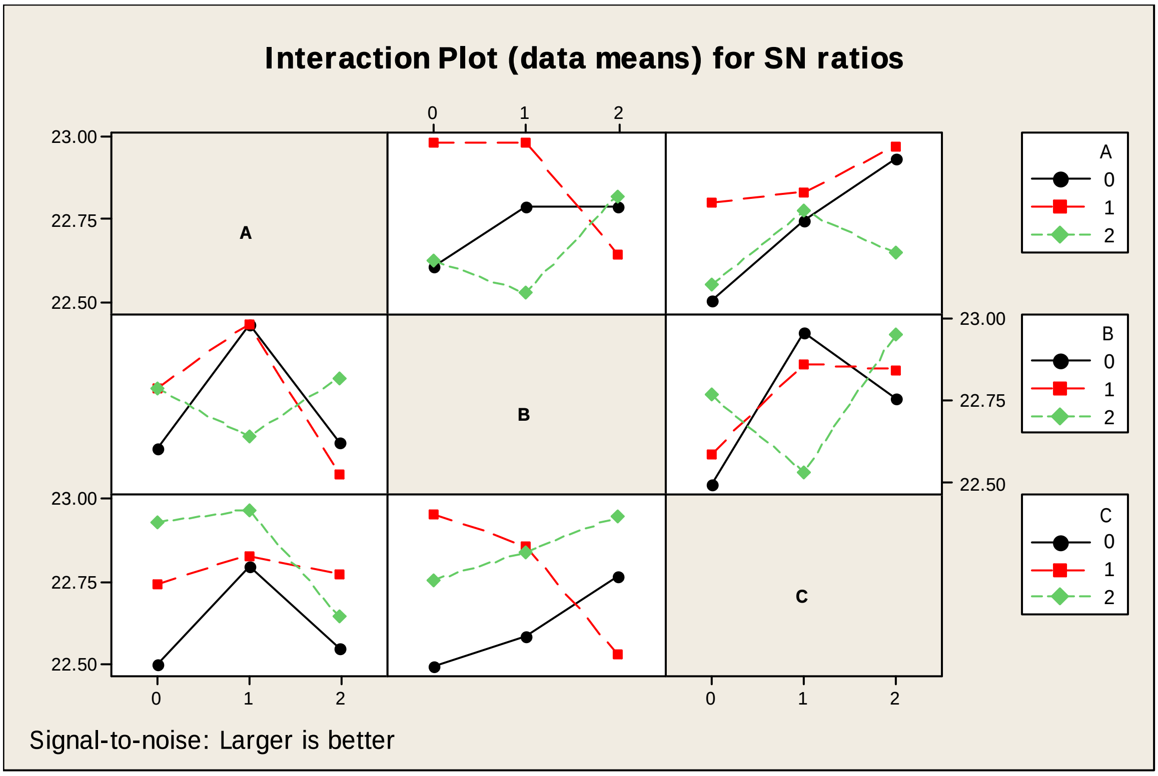


Figure 4: Interaction plot (data means) for S/N ratio

Each of the parameter was analyze using analysis of variance (ANOVA) which is standard statistical technique to provide a measure of confidence. Referring to the name itself, the technique does not analyze the data but rather determines the variance of the data. The confidence is measured from the variance of each parameter. The ANOVA computes quantities such as degree of freedom, sum of squares, variance and percentage of contribution as shown in table 5 below.

As can be seen on the ANOVA table, F-test indicates that some of the parameter doesn't achieve 90% confident level. For example, parameter B, AxC and E are less significant and should be pooled. Thus, $V_B$, $V_{AxC}$ and $V_E$ are combined to calculate a new error and pooled where it can be used to produce meaningful results. To increase the statistical significance of important factors, those factors with small variances should be pooled. Pooling is a process of disregarding an individual factor's contribution and then subsequently adjusting the contributions of the other factors. Taguchi recommends pooling factors until the error DOF is approximately half the total DOF of the experiment [17]. The results after pooling can be seen on the Table 6 below.

Table 5: ANOVA Table (Strength) before pooling

| COLUMNS | PARAMETER | FACTORS | DF | SUM OF SQUARES | VARIANCE | F | % CONTRIBUTION |
|---|---|---|---|---|---|---|---|
| 1 | A | Injection Pressure | 2 | 0.20862 | 0.10431 | 4.77683 | 10.82 |
| 2 | B | Injection temperature | 2 | 0.00374 | 0.00187 | 0.08572 | 0.19 |
| 3/4 | A x B | Interaction 1 | 4 | 0.43153 | 0.10788 | 4.94040 | 22.38 |
| 5 | C | Mold temperature | 2 | 0.26056 | 0.13028 | 5.96605 | 13.51 |
| 6/7 | A x C | Interaction 2 | 4 | 0.15074 | 0.03769 | 1.72579 | 7.82 |
| 8/11 | B x C | Interaction 3 | 4 | 0.46652 | 0.11663 | 5.34091 | 24.20 |
| 9 | D | Injection time | 2 | 0.26913 | 0.13457 | 6.16228 | 13.96 |
| 13 | E | Holding time | 2 | 0.04992 | 0.02496 | 1.14304 | 2.59 |
| | Error | | 4 | 0.08735 | 0.02184 | | 4.53 |
| | TOTAL | | 26 | 1.92812 | | | 100 |

Table 6: ANOVA table after pooling

| COLUMNS | PARAMETER | FACTORS | DF | SUM OF SQUARES | VARIANCE | F | % CONTRIBUTION |
|---|---|---|---|---|---|---|---|
| 1 | A | Injection Pressure | 2 | 0.20862 | 0.10431 | 4.29030 95% | 8.3 |
| 2 | B | Injection temperature | 2 | 0.00374 | Polled | | |
| 3/4 | A x B | Interaction 1 | 4 | 0.43153 | 0.10788 | 4.43713 97.5 % | 17.34 |
| 5 | C | Mold temperature | 2 | 0.26056 | 0.13028 | 5.35845 97.5 % | 10.99 |
| 6/7 | A x C | Interaction 2 | 4 | 0.15074 | Polled | | |
| 8/11 | B x C | Interaction 3 | 4 | 0.46652 | 0.11663 | 4.79702 97.5 % | 19.15 |
| 9 | D | Injection time | 2 | 0.26913 | 0.13457 | 5.5347 97.5% | 11.44 |
| 13 | E | Holding time | 2 | 0.04992 | Polled | | |
| | Error | | 12 | 0.29176 | 0.024313 | | 32.78 |
| | TOTAL | | 26 | 1.92812 | | | 100 |

Continuity from the significant parameter which are A, AxB, C, BxC and D, the confident interval (C.I) is calculated. C.I represented the variation of the estimated value of the main effect of a factor of the result at the optimum at a confidence level used for the F values. The C.I of estimates of the factor effect shown in Table 7 is calculated with equation below [18]

$$CI = \pm\sqrt{\frac{F_\alpha(f_1, f_2) \times V_e}{N_e}} \qquad (2)$$

Where, $F_\alpha$ ($f_1$, $f_2$) is the variance ratio for DOF of $f_1$ and $f_2$ at level of significance α. The confidence level is (1-α), $f_1$ is the DOF of mean (usually equal to 1) and $f_2$ is the DOF for the error. Variance for error terms is $V_e$ and number of equivalent replication is given as ratio of number of trials (1+DOF of all factors used in the estimate). The confident interval will indicate the maximum and minimum levels of the optimum performance and it is shown as the respected result as optimum performance in Table 7 below.

Optimum performance calculation is based from significant parameter A, AxB, C, BxC and D. The highest S/N ratio for those parameter are used to estimate the range of optimum performance. However, parameter $A_1$ is eliminated as $A_1xB_1$ has higher S/N ratio compare to $B_0xC_1$. Thus $B_0xC_1$ is also eliminated as the calculation only involved one parameter even after considering the interaction.

Table 7: Estimate of performance as the optimum design after pooling.
(Characteristics: Larger the Better)

| $\overline{A_1}\ \overline{B_1}\ \overline{C_1}\ \overline{D_0}$ | |
|---|---|
| Optimum Performance Calculation: $\bar{T} + (\overline{A_1B_1} - \bar{T}) + (\overline{C_2} - \bar{T}) + (\overline{B_0C_1} - \bar{T}) + (\overline{D_0} - \bar{T}) + (\overline{A_1} - \bar{T})$ <br> 22.7508 + (22.9832-22.7508) + (22.8509-22.7508) + (22.9575-22.7508) + (22.8918-22.7508) + (22.8681-22.7508) = 23.5483 | |
| Current grand average performance | 22.7508 |
| Confident interval at the 90% confidence level | ±0.20714 |
| Expected result at optimum performance, μ | 23.34116 dB < μ < 23.75544 dB |

Further analysis is to predict the quality characteristics based from optimum performance calculation. Based from the optimum injection parameter after pooling, the confirmation experiment should be within the range 23.34116 dB and 23.75544 dB. Table 8 below shows the green strength of the green part molded by using the optimum injection parameter which are $A_1B_1$, $C_2$ and $D_0$ . The results from table 8 are acceptable as the S/N ratio just 0.02 dB above the minimum level.

Table 8: Confirmation experiment

| REP 1 | REP 2 | REP 3 | REP 4 | REP 5 | REP 6 | REP 7 | REP 8 | REP 9 | REP 10 | S/N(Larger the better) |
|---|---|---|---|---|---|---|---|---|---|---|
| 15.48 | 15.19 | 14.85 | 14.46 | 14.68 | 14.35 | 14.37 | 15.49 | 14.29 | 14.24 | 23.36 |

Note: The holding time is varied at random

## 4. CONCLUSION

Taguchi's orthogonal array is designed to improve the quality of products and processes where the performance depends on many factors while analysis of variance (ANOVA) establishes the relative significance to the individual factors and the interaction effects. From ANOVA, the parameters that shows significant are injection pressure (A), mold temperature(C), injection time (D) and the interaction between injection pressure with mold temperature (AxC) and injection temperature and mold temperature (BxC). All these parameters have confident level above 90% by using F-test. The optimum parameter obtain from ANOVA are acceptable where the range of optimum performance between 23.34116 dB and 23.75544. The results meet the requirement when S/N ratio (23.36 dB) from confirmation experiment is within the range and meet 90% confident level.

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