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EFFECT OF INJECTION PARAMETERS ON GREEN PART MECHANICAL PROPERTIES FOR METAL INJECTION MOLDING

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Abstract- *This study aims to investigate the effect of the injection molding parameters on green part's mechanical properties. Taguchi statistical method is used for experimental design and analysis. Green parts were characterized through morphological analysis, density measurement, and tensile test. The investigation focused on the observation of green part's mechanical properties corresponding to the injection temperature and pressure. Comparatively better mechanical properties of the green part were observed at 53.3 MPa injection pressure and 160 ^{0}C injection temperature. The experimental and analytical results were validated through confirmation experiment. The investigation demonstrates the properties of the green part produced through injection molding process.*

Keywords: MIM, Binder, Green Part and ANOVA.

1. INTRODUCTION

Metal injection molding (MIM) is a manufacturing technique that combines the benefit of powder metallurgy and plastic injection molding [1]. This technique scopes the production of metal parts of small size and complex geometry.

Numbers of parameters like pressure, temperature, time, speed etc. affect the green part as well as final part quality [2-4]. Ani et al. [2] reported 110 MPa injection pressure and 160 0C injection temperature as optimum for a higher density of alumina-zirconia based green part. Jamaludin et al. [3] reported the proportional effect of injection temperature on density and strength of bimodal stainless steel green part. Packing time is influential to the surface quality of the injected component [4]. However, consistency regarding green part quality is hindered due to some challenges like powder-binder separation, incomplete mold filling, sink mark, weld line etc. Control and monitoring of process parameters have been discovered as an approach for eliminating or minimizing the product defects.

The present study aims to investigate the influence of injection pressure and temperature on green part's mechanical properties and to optimize injection parameters for higher green strength.

2. MATERIALS AND METHODS

2.1 Materials

Silver gray colored aluminum (Al) powder of 99.8% purity, 19.82 µm particle size, spherical shape, and 2.699 g/cm^3 relative density was used to formulate feedstock. Three component binder system consisting high-density polyethylene (HDPE), paraffin wax (PW), and stearic acid (SA) was used in the ratio of 50:46:4 to prepare the feedstock [5], [6]. Physical properties of the binder elements used in the present study are given in Table 1.

Table 1: Characteristics of binder components

Properties	HDPE	PW	SA
Melting Temp. [^{0}C]	120	57	68
Density [g/cm^3]	0.95	0.75	0.84
Supplier	Nova Scientific		

2.2 Methods

The mixing of Al powder and binder components was carried out using an in-house built mixer (figure 1). Conditions like 58 vol.% powder concentration, 120^{0}C mixing temperature, and 43 rpm mixing speed were used for powder-binder mixing as well as for feedstock preparation [7].

Taguchi L9 (32) orthogonal array design (as shown in Table 2) was created for experimental investigation of injection molding (IM) process with injection pressure and temperature. Injection molding process was accomplished using a custom made injection molding machine [8]. Injection parameters i.e. injection pressure and temperature were varied conforming to the orthogonal array design (Table 2). Fixed injection time 5s was considered for all run of IM process [9].

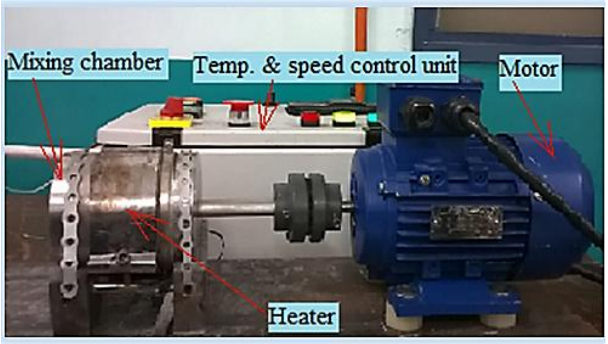

Fig. 1: Custom-made mixer machine

Table 2: L9 (3^3) Taguchi orthogonal array of DOE

Run	P_{inj} [MPa]	T_{inj} [^{0}C]
1	49.8	150
2	53.3	160
3	56.9	170
4	53.3	170
5	56.9	150
6	49.8	160
7	56.9	160
8	49.8	170
9	53.3	150

Optimization of injection parameters was conducted by using Taguchi DOE technique through analyzing the experimental results. The S/N ratio approach was utilized for parameter optimization as it is considered as performance criteria or quality index in Taguchi technique [10]. 'Larger-is-better' approach (Eqn. (1)) was considered for S/N ratio calculation as well as for parameter optimization as the response 'green strength' is expected to be higher.

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

The accuracy of the result of Taguchi optimization was checked by executing the confirmation experiment using optimum level of parameters. The predicted S/N ratio was calculated by using Eqn. (2) and compared to the experimental S/N ratio to validate the Taguchi optimized result. The result of confirmation experiment should be within the range of a $\pm$ standard deviation (known as confidence interval) from the predicted result which was calculated using Eqn. (3) [11].

$$S/N = \overline{S/N} + \sum_{i=1}^{n}\left(S/N_i - \overline{S/N}\right) \quad (2)$$

$$CI = \left| N_{\alpha/2} \times \frac{S}{\sqrt{m_e}} \right| \quad (3)$$

Where, $\overline{S/N}$ is mean of total *S/N* ratio, S/N_i is the S/N ratio at optimum parameter level, n is the observation numeral, and m_e is the ratio of total experimental numeral and the total degree of freedom. In the present study, 95% confidence level was considered to calculate $N_{\alpha/2}$. The influence of injection parameters on green strength was determined through analysis of variance (ANOVA) which was done on the basis of the recommendations made by the researchers [10,12].

The microstructure of the green part was observed through field emission scanning electron microscope (FESEM; FEI Quanta 450 FEG, Australia) to analyze its homogeneity. This observation was carried out by its sampling the green part from the different portion. Green part's desnsity was determined according to the Archimedes method using the formula given in Eqn. (4).

$$Density, \rho = \frac{weight_{air}}{weight_{air} - weight_{water}} \times \rho_{water} \quad (4)$$

The weight of the product (green part) in the air and water was measured by using Electronic Balance (AY220, SHIMADZU, JAPAN). The tensile stress of the green part was determined by using the dual column universal testing machine (INSTRON 3369, Singapore).

3. RESULT AND DISCUSSION

The green part produced through injection molding process and the morphology of the green part are shown in figure 2 and figure 3, respectively. The morphology illustrates that the Al powders are equally distributed in the binder matrix. Similar morphology was observed for all green part.

Fig. 2: Green Part

3.1 Density of the Green Part

The density of the green parts increases with the increase of injection pressure (P_{inj}) and temperature (T_{inj}) while it decreases slightly after 53.3 MPa and 160^{0}C (figure 4). Ani et al. [2] reported the similar effect for ceramic injection molding process. Green density is affected by higher injection pressure and temperature due to thermoplastic binder's higher compressibility at higher pressure and increasing part shrinkage at higher temperature [13]. In the present study, higher green density (87.44 to 89.14% of the powder density) was obtained as expected for MIM green part. Ani et al. [2] found green density as 90.1% of the theoretical density. Therefore, the green density obtained in the present study is close to the previous researchers finding.

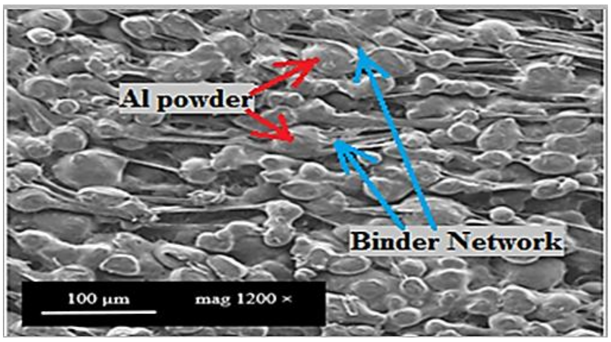

Fig. 3: Morphology of the green part

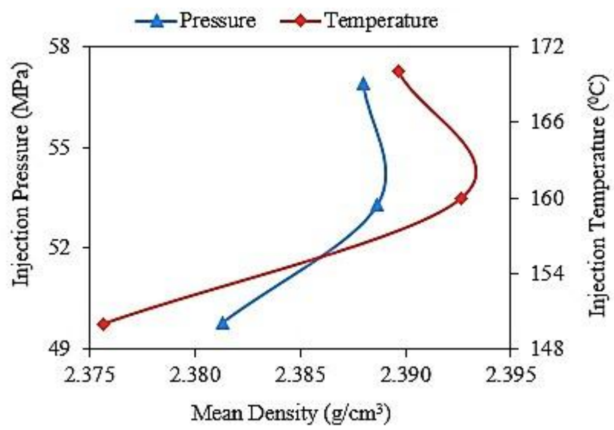

Fig. 4: Density of the green part corresponding to injection pressure and injection temperature

3.2 Green Strength and Parameter Optimization

Green strengths observed through tensile test are listed in Table 3. The highest green strength was observed to be 8.53 MPa. Wu and Wei [14] reported the strength of aluminum green part as about 11 MPa which is close to the finding of the present study. S/N ratio for green strength was calculated considering 'larger-is-better' approach and is shown in Table 3. Response plots for mean strength and mean S/N ratio corresponding to individual parameters are shown in figure 5.

Figure 5(a) depicts that the part strength as well as the S/N ratio increases with the increase of injection pressure (Pinj) initially while, after a peak value, strength becomes almost constant as P_{inj} increases. Injection pressure assists the feedstock flow to the mold cavity. Higher P_{inj} causes more feedstock injection into the mold until it becomes too dense. Therefore, the part density as well as the part strength increases with the initial increase of Pinj while both part density and strength remain almost constant with the further increase of injection pressure after its optimum value [2].

Defects in the injection molded part can be avoided by maintaining the injection temperature at its optimum level. Injection temperature also affects the mechanical properties of the materials indirectly. Figure 5(b) illustrates that strength of the green part increases with the increase of injection temperature initially, while after having attained a peak value, green strength decreases with further increase of T_{inj}. During IM process, feedstock expands due to injection temperature while the part shrinkage occurs in the mold cavity due to immediate cooling after injection [2], [13]. Therefore, it can be hypothesized that too high injection temperature may lead to higher shrinkage in the molded part which affects the part density as well as strength as observed in the present study. Therefore, 53.3 MPa injection pressure and 160^{0}C injection temperature can be considered as optimum injection parameters as higher green strength as well as larger S/N ratio was observed for this pressure and temperature (Figure 5(a) and Figure 5(b)).

Table 3: Green Strength and S/N ratio

Experiment	*GS* [MPa]	*S/N* ratio [dB]	Predicted *S/N* ratio [dB]
1	4.05	12.15	13.32
2	8.53	18.61	18.09
3	6.59	16.36	17.49
4	6.93	16.81	17.56
5	6.60	16.38	15.45
6	5.74	15.18	15.89
7	8.16	18.22	18.02
8	7.28	17.24	15.36
9	6.14	15.75	15.52
Confirmation Exp.	8.79	18.63	19.09

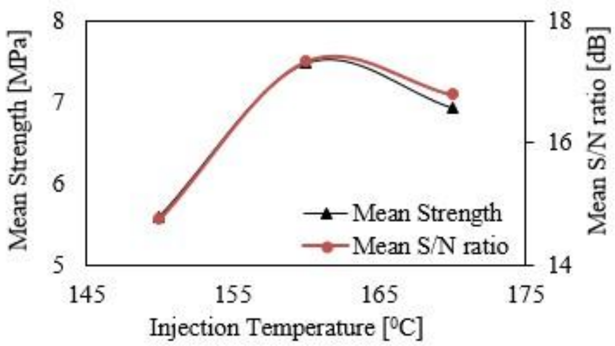

Fig. 5(a): Response graph for injection temperature

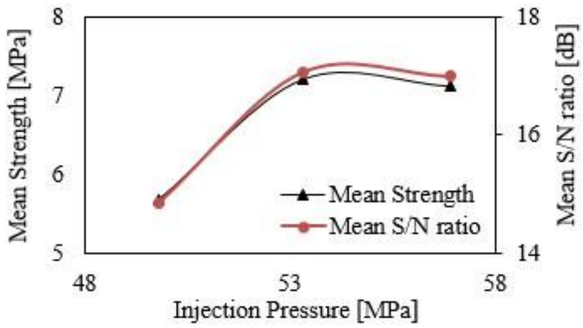

Fig. 5(b): Response graph for injection pressure

3.3 Confirmation Experiment

To validate the Taguchi optimized results, additional injection molding experiments (confirmation experiment) were carried out by setting injection pressure and temperature at optimum level and repeated for three times. The response of confirmation experiment and predicted S/N ratio are given in Table 3. The predicted S/N ratio at optimum injection conditions was observed to be 18.0983 dB (Table 3). The error between the S/N ratio of confirmation experiment and predicted S/N ratio was found to be 2.86 % which satisfy 95% confidence level. Confidence interval (standard deviation) for 95% confidence level was found to be 1.0723. Therefore, the S/N ratio from confirmation experiment (CE) for IM process should be within the range of 18.0983±1.0723 dB at 95% confidence level. From Table 4, the S/N ratio for CE is 18.6318 which lies in the range of 18.0983±1.0723 dB Hence, 95% confidence level is satisfied. Therefore, the optimized results can be considered as reliable for MIM process [15].

3.4 Analysis of Variance

Analysis of variance (ANOVA), the computational technique was used to quantitatively estimate the relative contribution of the injection parameters on green strength (Table 4). According to Table 4, both injection pressure and temperature are significant parameters (F-ratio > 4) for green part strength [10].

Table 4: ANOVA for S/N ratio for green part strength

Factor	Sum square	DOF	Variance	F-ratio	Percent Contribution
P_{inj}	11.23	2	5.62	22.50	38.83
T_{inj}	16.69	2	8.35	33.45	57.72
Error	1.00	4	0.25		3.45
Total	28.93	8			100

In term of percent contribution, T_{inj} was found as the most contributing parameter with 57.72% contribution to green strength. Meanwhile, the contribution of P_{inj} on green strength was found to be 38.83%.

4. CONCLUSION

Effects of injection pressure and temperature on the green part's mechanical properties (density and strength of the green part) were studied for the metal injection molding process. The findings of the study are summarized as follow:

- Density and strength of the green part increase with the increase of injection pressure and temperature and reach a peak value at the optimum level of the injection parameters. After optimum pressure, green density decreases and green strength remains almost constant with further increase of injection pressure. In contrary, both green density and strength decrease at the temperature higher than its optimum value.
- Optimum parameters of injection molding process are found to be 160^0C injection temperature and 53.3 MPa injection pressure.
- The contribution of injection pressure and temperature on green strength are found to be 38.83% and 57.72%, respectively.

5. ACKNOWLEDGEMENT

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