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IMPACT OF INJECTION MOULDING PROCESS PARAMETERS ON ULTIMATE TENSILE STRENGTH OF PARTS PRODUCED BY METAL INJECTION MOULDING

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ABSTRACT

This research work is focused on optimization of the injection moulding process parameters in MIM process to achieve high tensile strength. Taguchi Technique is used to model the experimental process because of its statistical ability to analyse the effect of parameters by conducting a very few experiments as per the designed orthogonal arrays. The significant factors as well as their contribution in the output are observed by using analysis of variance (ANOVA). The confidence level of the significant factors is found by using F-values. The effect of interaction of process parameters is observed by using contour curves. For this experiment Taguchi L_{27} orthogonal array consisting of 27 experiment trials with 8 experimental parameters is used to obtain the signal to noise ratio (S/N ratio). The solvent and thermal debinding techniques are used in this work to remove the binders effectively. The brown parts were first presintered at 900 °C then sintered was carried out in vacuum conditions at 1360 °C.

Keywords: Injection Moulding, Metal Injection Moulding, Powder Injection Moulding, Taguchi Technique, Single objective optimisation

I. INTRODUCTION

Metal injection moulding (MIM) is an emerging technology to process metal powders into parts of desired shapes. The MIM process combines the traditional shape-making capability of plastic injection moulding and materials flexibility of powder metallurgy [1]. The process consists of four main steps: mixing, injection moulding, debinding and sintering [2]. During injection moulding a green part with the desired shape is formed by the feedstock flow into a mold under pressure. After moulding, the binder holds the particles in place. The binder is then removed in the debinding step and the debound part is sintered to achieve the required mechanical properties. The geometrical accuracy and mechanical properties of the final parts after sintering depend strongly on the process parameters in the different stages [3,4]. Although the MIM process offers many advantages, it requires proper moulding condition. The classical Design of Experiment (DOE) technique has been used by many authors [5-7] for optimization of single process parameters at a time. In order to obtain high efficiency in the planning and analysis of experimental data, the Taguchi method is recognized as a systematic approach for design and analysis of experiments to improve product quality [8-9]. The Taguchi method has been applied by many authors to investigate and optimize the process parameters [10-14]. The majority of previous

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investigations in MIM have focused on the sintering parameters and the amount of metal powder in the mixture. The effect of the injection moulding parameters on tensile strength of the parts produced by MIM has not yet been thoroughly investigated. The objective of this paper is to find the significant factors and their contribution in tensile strength of final part.

II. MATERIALS AND METHODS

To make the working material, the SS316L stainless steel powder was mixed with the binder comprised of polyethylene glycol (PEG), polymethyl methacrylate (PMMA), paraffin wax and stearic acid (SA). Paraffin wax is used to decrease the feedstock viscosity and to increase replication ability of the feedstock. The main advantage of using PMMA/PEG binder is that it can be removed from the mouldings in a comparatively short time. The SS316L metal powder used in this research was supplied by Osprey®. The chemical composition of the steel is presented in Table 1. The size distribution of metal powder is given in Table 2. The percentage concentration of constituents by weight and densities are given in Table 3. The details of the binder ingredients are given in Table 4.

The metal powder and binder were mixed thoroughly for 90 minutes with the help of a Brookfield Rheometer in the desired proportion under precise weight and temperature control condition. The calculated amount of metal powder, PMMA, PEG, paraffin wax and stearic acid were weighed and mixed together. The mixing was carried out at 160 °C and 40 rpm to achieve a homogeneous distribution of the powder particles and binder in feedstock. After thorough mixing, the mixture was first dried in air at ambient temperature for 2 hours and then in an oven at a temperature of 50 °C for 1 hour. After compounding the feedstock was allowed to cool to at ambient temperature and then granulated in a rotary feedstock granulator.

III. PRODUCTION OF TEST SPECIMEN

A four-cavity mould was specifically designed and made by National Small Industries Corporation (NSIC), Aligarh according to the specifications of the Demag injection moulding machine. The cavities were created in accordance with MPIF Standard 50.

IV. FIGURES AND TABLES

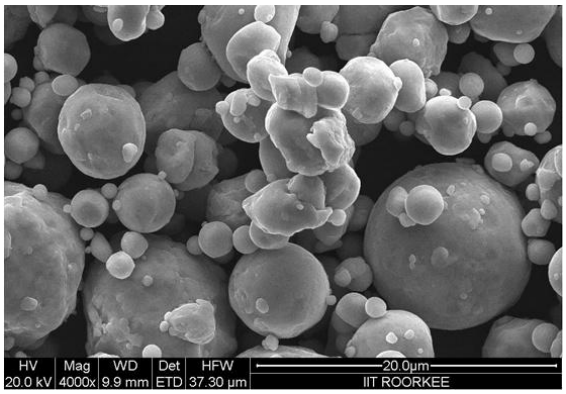

Fig 1 SEM micrographs of SS316L powder used for study

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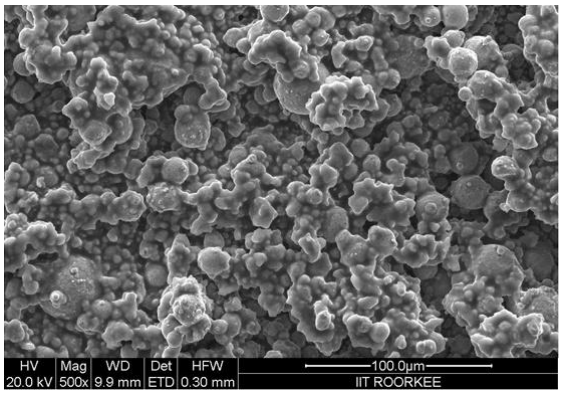

Fig 2 SEM micrographs of blended powder feedstock made for study

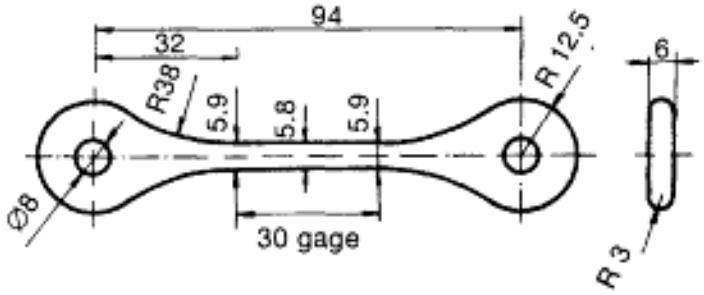

Fig 3 MPIF-50 based tensile test bar (specimen size before sintering)

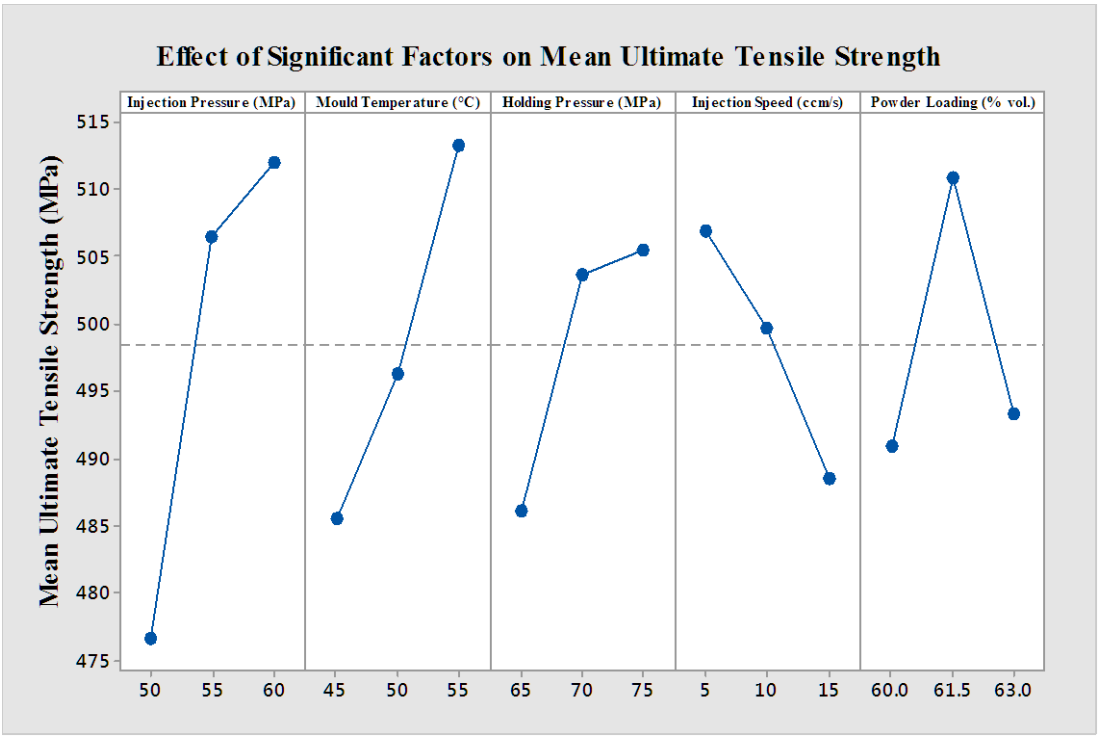

Fig 4 Main Effects Plot for Mean values of Ultimate Tensile Strength

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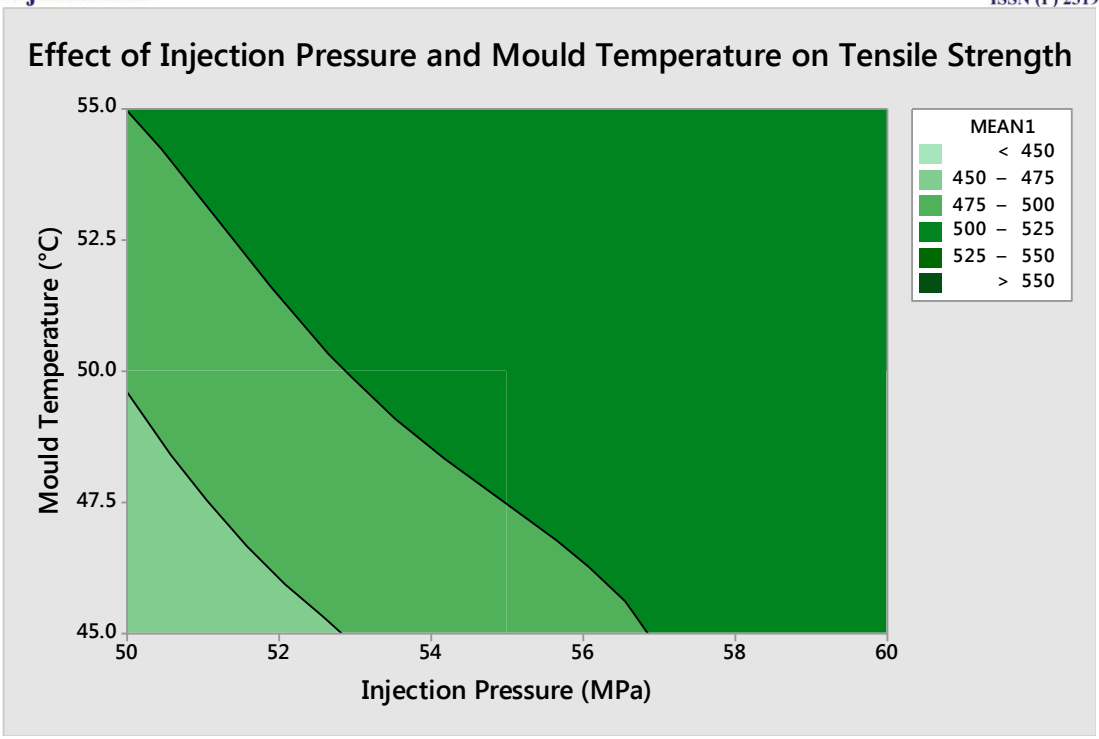

Fig 5 Contour Curve for Injection Pressure and Mould Temperature

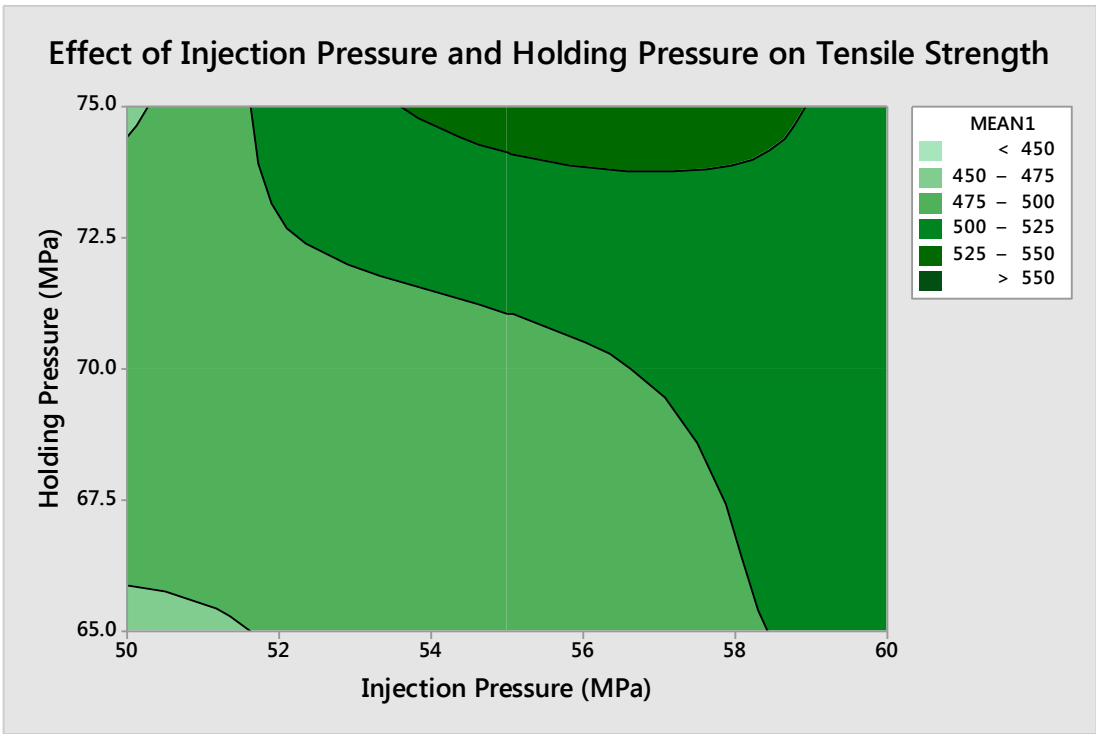

Fig 6 Contour Curve for Injection Pressure and Holding Pressure

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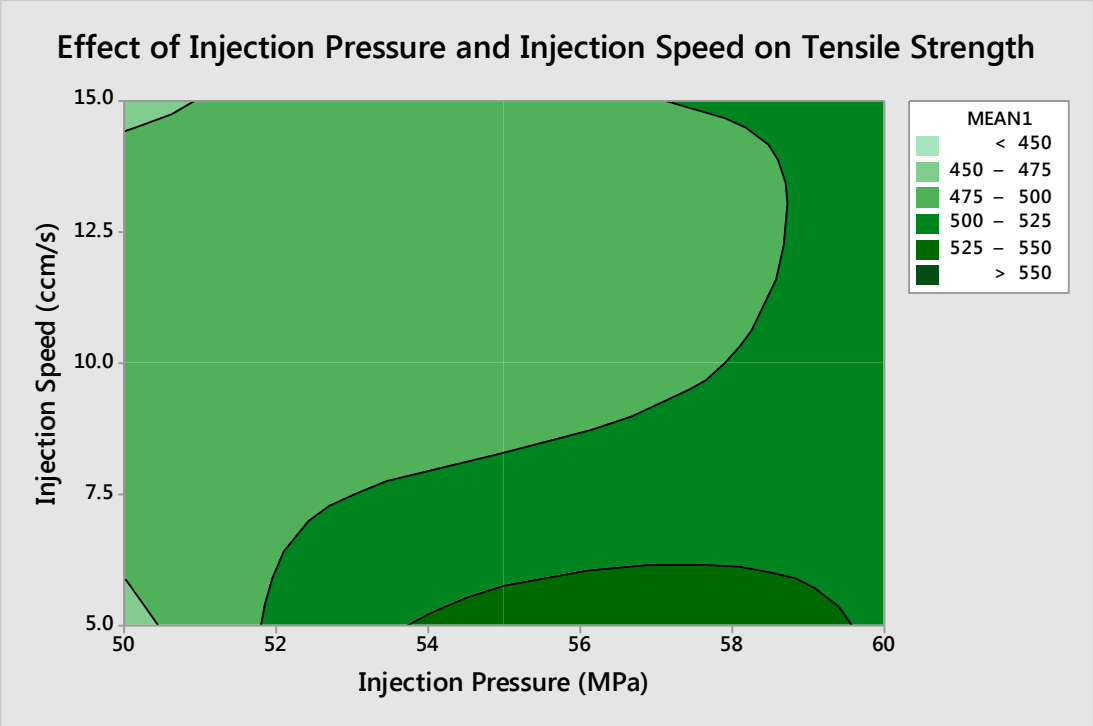

Fig 7 Contour Curve for Injection Pressure and Injection Speed

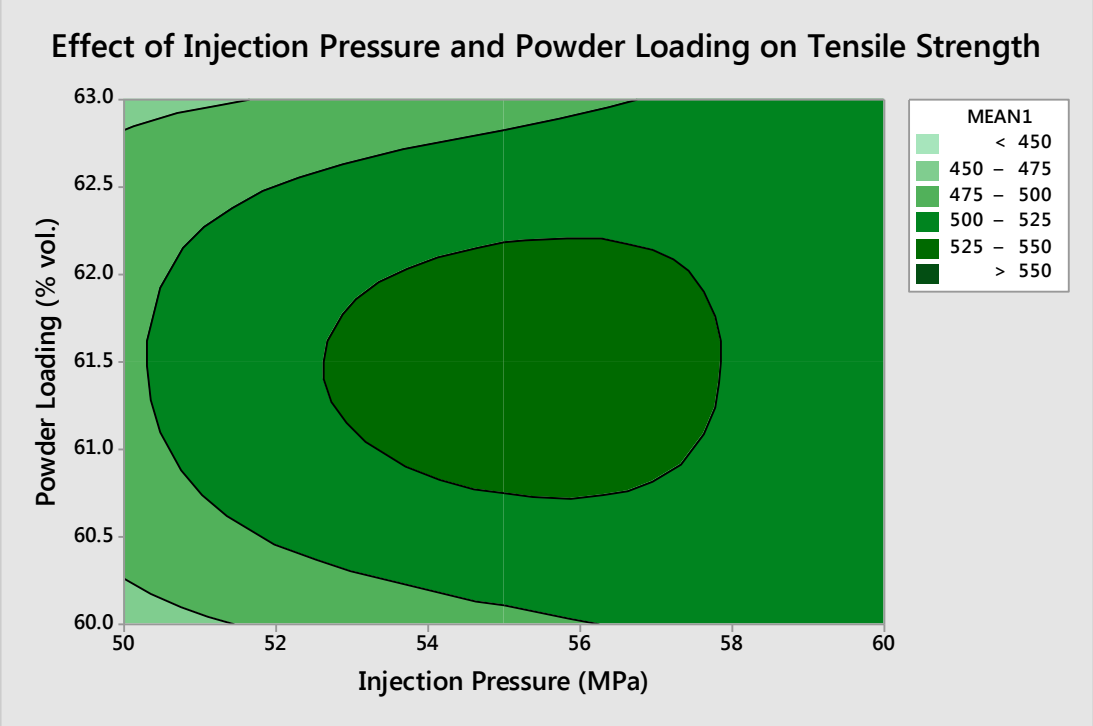

Fig 8 Contour Curve for Injection Pressure and Powder Loading

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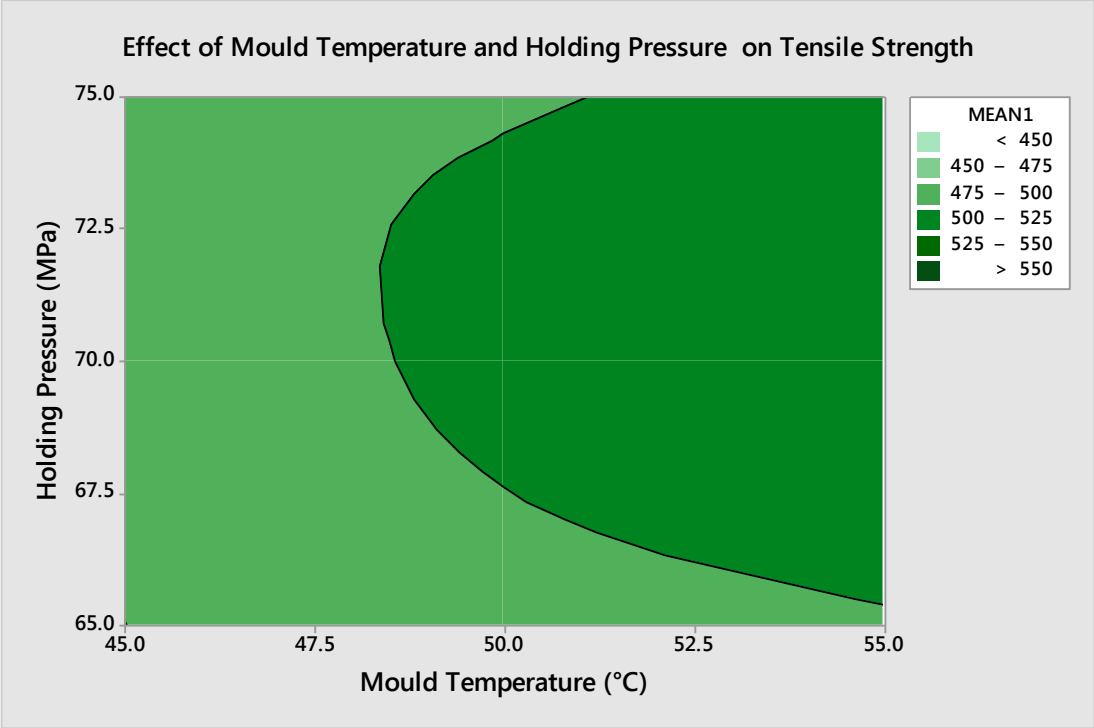

Fig 9 Contour Curve for Mould Temperature and Holding Pressure

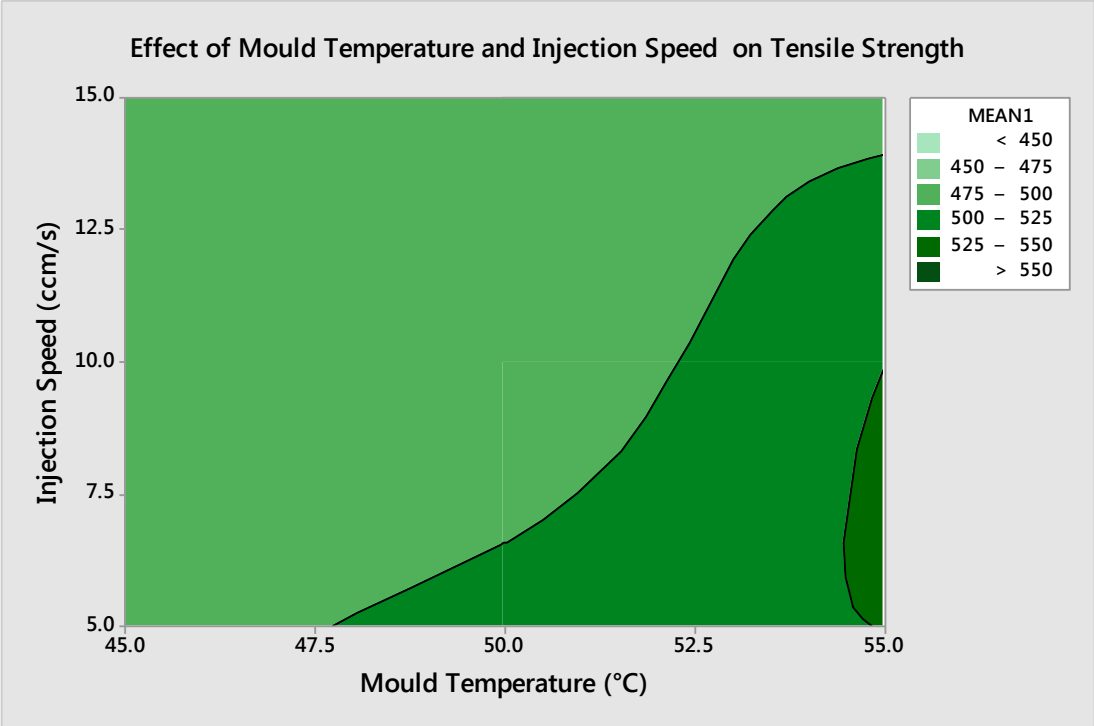

Fig 10 Contour Curve for Mould Temperature and Injection Speed

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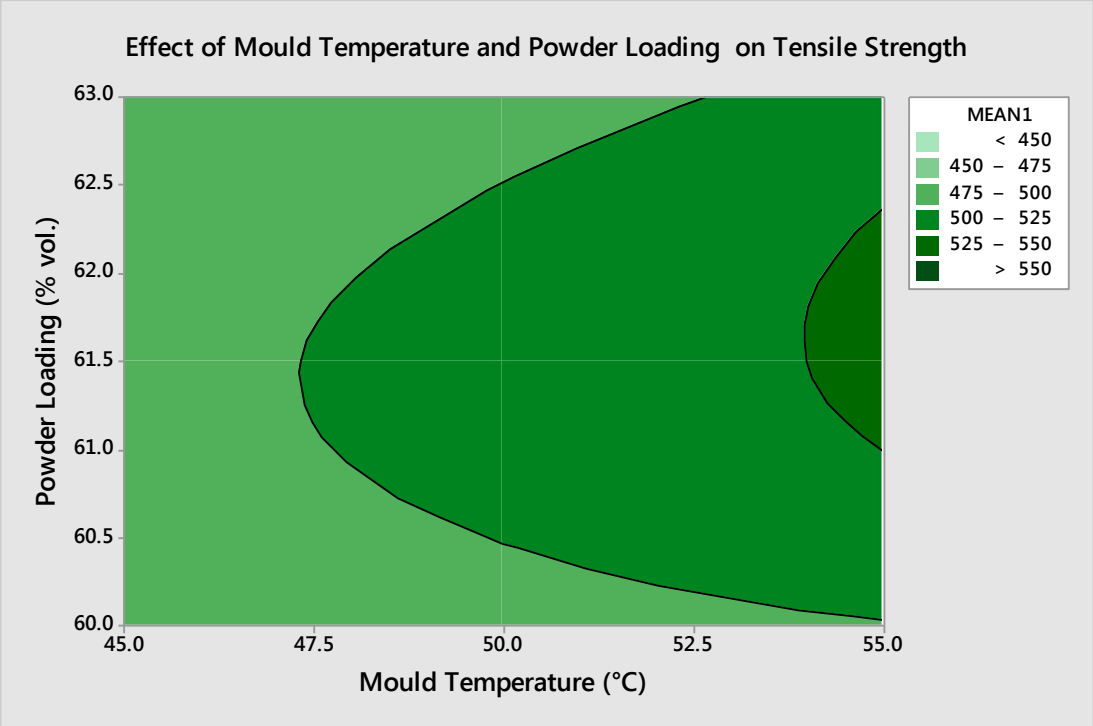

Fig 11 Contour Curve for Mould Temperature and Powder Loading

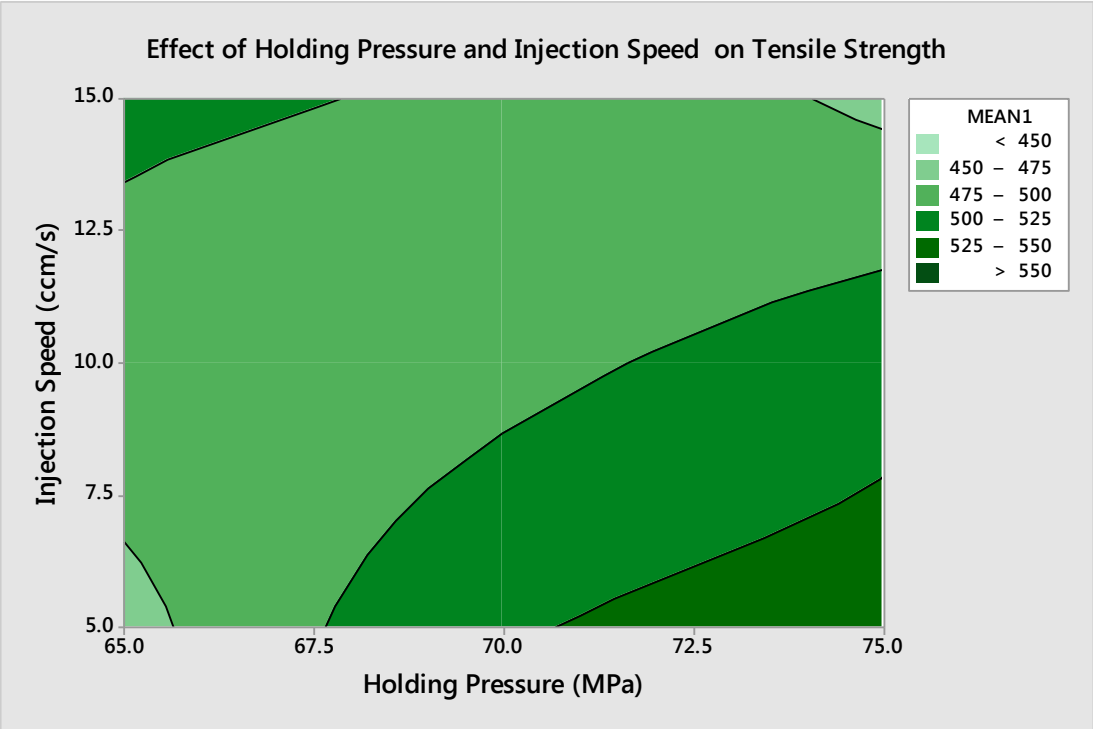

Fig 12 Contour Curve for Holding Pressure and Injection Speed

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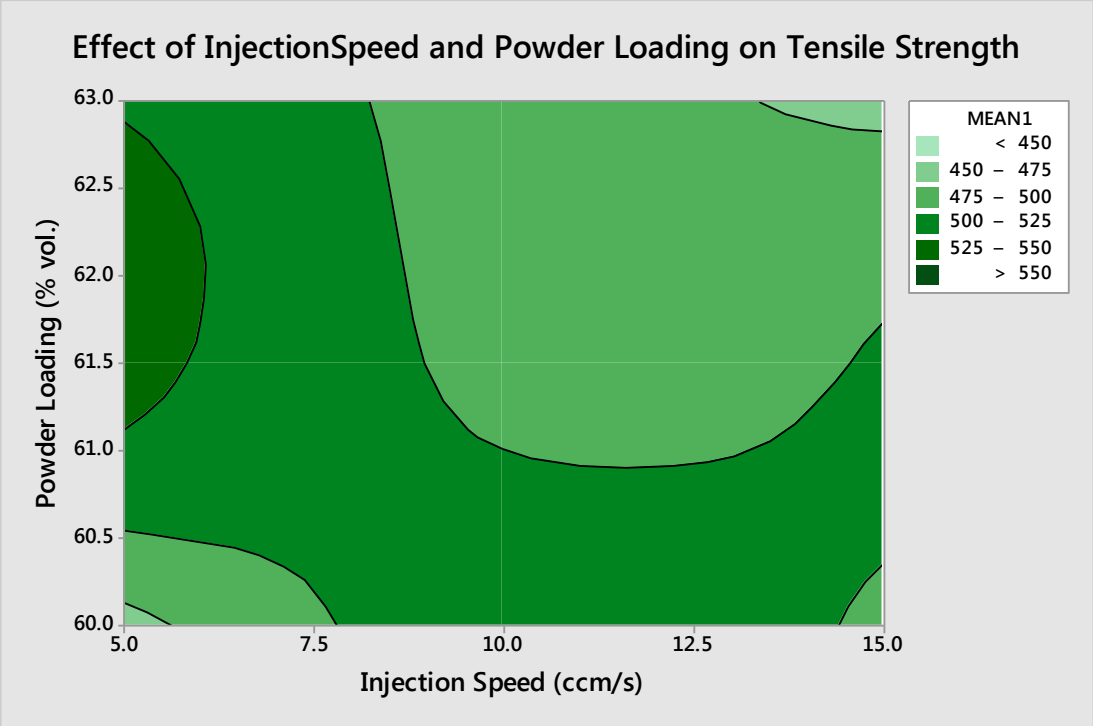

Fig 13 Contour Curve for Injection Speed and Powder Loading

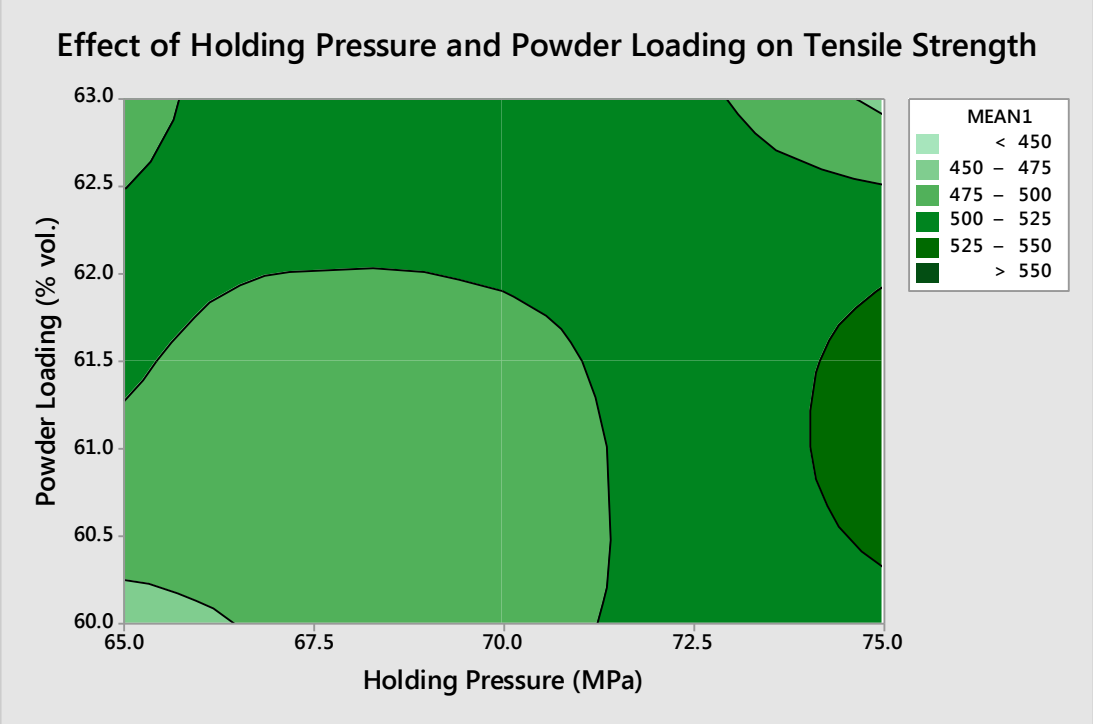

Fig 14 Contour Curve for Holding Pressure and Powder Loading

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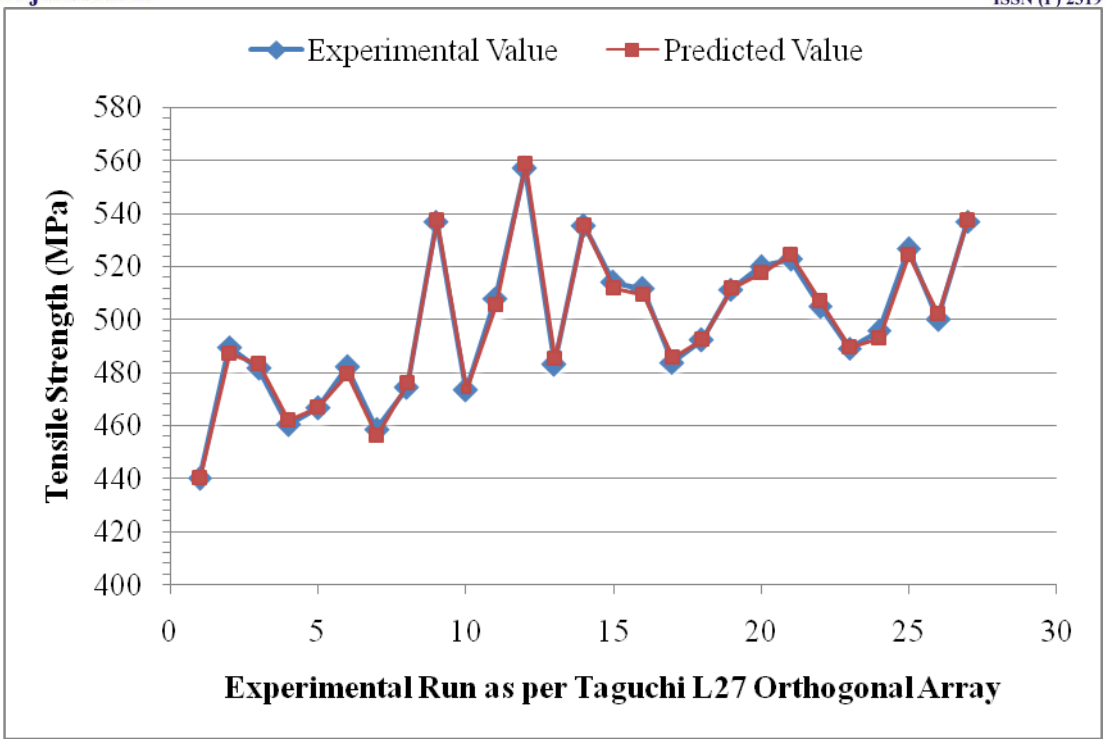

Fig 15 Comparison of experimental and predicted mean values

Table 1: Composition of SS316 L powder (Report given by Osprey® alongwith the powder)

Element %								
C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**Fe**
0.018	0.55	1.5	0.031	0.017	16.9	11.6	2.2	balance

Table 2: Size distribution of SS316 L powder (Report given by Osprey®)

Powder Tests report by Sandvik Osprey Ltd.				
d10	d50	d90	-53 µm	Tap Density
3.9 µm	13.0 µm	36.6 µm	99.2 %	5.0 gm/cc

Table 3: Theoretical density of constituents of SS316 L powder

Element	Percentage concentration	Theoretical Density
C	0.018	2.267
Si	0.55	2.33
Mn	1.5	7.47
P	0.031	1.823
S	0.017	1.96
Cr	16.9	7.14
Ni	11.6	8.9
Mo	2.2	10.28
Fe	67.184	7.874
SS 316 L	100	7.88146

Table 4: The binder ingredients

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Designation	Manufacturer	Amount (%)	Melting temperature °C	Boiling point °C	Density (gm/cc)
PMMA	Vetec	65	157.77	200	1.19
PEG	Rankem	08	35-40	250	1.22
Paraffin Wax	Thermo Fischer Scientific	25	60-62	370	0.90
Stearic acid (SA)	Thermo Fischer Scientific	02	70.1	383	0.94

TABLE 5: Response Table for Mean values of Tensile Strength (N/mm^2)

Level	P_i	T_i	T_m	P_h	v_i	φ	t_h	t_c
1	476.7	500.4	485.6	486.1	506.9	490.9	501.1	500.6
2	506.5	492.4	496.4	503.6	499.6	510.9	495.4	499.1
3	512.0	502.4	513.2	505.5	488.6	493.3	498.6	495.5
Delta	35.3	10.0	27.6	19.4	18.3	20.0	5.6	5.0
Rank	1	6	2	4	5	3	7	8

TABLE 6: Response Table for Signal to Noise Ratios (Larger is better)

Level	P_i	T_i	T_m	P_h	v_i	φ	t_h	t_c
1	53.54	53.96	53.69	53.70	54.06	53.78	53.96	53.95
2	54.06	53.80	53.89	54.01	53.94	54.13	53.86	53.93
3	54.15	53.98	54.16	54.04	53.75	53.84	53.92	53.87
Delta	0.61	0.18	0.47	0.34	0.30	0.36	0.09	0.08
Rank	1	6	2	4	5	3	7	8

TABLE 7: ANOVA Table using S/N ratios for Ultimate Tensile Strength

Factors/ Source	DOF, v	Sums of squares	Variance, Vn	Variance Ratio, Fn	Significance Level, α	Pure Sum Square	Contribution, P in %
P_i	2	1.9718	0.9859	10.95	0.05	1.7918	29.23
T_i	(2)	0.1674	Pooled				
T_m	2	0.9980	0.4990	5.54	0.05	0.818	13.34
P_h	2	0.6380	0.3190	3.54	0.05	0.458	7.47
v_i	2	0.4220	0.2110	2.34	0.05	0.242	3.95
φ	2	0.6604	0.3302	3.67	0.05	0.1502	2.45
t_h	(2)	0.0410	Pooled				
t_c	(2)	0.0328	Pooled				
Pi x Ti	(4)	0.6082	Pooled				

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Pi x Tm	(4)	0.5702	Pooled				
Residual Error	16	1.4402	0.0900				43.56
Total	26	6.1304					100

TABLE 8: Factor levels for predictions

Injection Pressure (MPa)	Mould Temperature (°C)	Holding Pressure (MPa)	Injection Speed (ccm/s)	Powder Loading (% vol.)
60	55	75	5	61.5

Table 9: Results of confirmation experiments

Characteristic	Replication at optimum process parameters					Average(N/mm^2)	Minitab predicted value(N/mm^2)
	R1	R2	R3	R4	R5		
Ultimate Tensile Strength	554.76	550.17	546.98	545.11	555.03	550.41	554.95

V. CONCLUSION

The main effects of variable controllable parameters can be studied by the level average response of mean data and S/N ratio. The mean values and average S/N ratios of ultimate tensile strength for each parameter at all three levels are given in Tables 5 and 6 respectively. The analysis is made by the mean and S/N data at each level of each parameter. The level average response required for analysis of the trend of performance characteristics with respect to the variation of the factor under study is shown in Fig 4. From Table 6, the highest value of S/N ratio is noted for every factor to find the optimum level of process parameters for highest ultimate tensile strength. The optimum level without considering the interaction factors can be noted as: $(\text{injection pressure})_3$ $(\text{injection temperature})_3(\text{mould temperature})_3$ $(\text{holding pressure})_3$ $(\text{injection speed})_1$ $(\text{powder loading})_2$ $(\text{holding time})_1$ $(\text{cooling time})_1$. If the interaction factors are also taken into consideration the maximum value of S/N for the interaction of injection pressure and injection temperature occurs at $(P_i)_3(T_i)_3$ while that for the interaction of injection pressure and mould temperature occurs at $(P_i)_2(T_m)_3$. From Table 6, it can further be noted from the rank of the parameters that variation in the value of S/N ratio with the change in the value of parameter is maximum for injection pressure and least for cooling time.

Since, only P_i, T_m, P_h, v_i, and φ are the significant factors, the optimum value of ultimate tensile strength will depend only on these factors and could be estimated by eq. (1) at the optimum levels shown in Table 4.2.

$$\mu_{TS} = \bar{T} + [(P_i)_3 - \bar{T}] + [(T_m)_3 - \bar{T}] + [(P_h)_3 - \bar{T}] + [(v_i)_1 - \bar{T}] + [(\varphi)_2 - \bar{T}] \quad (1)$$

Where,

$\bar{T}$ is the overall mean of tensile strength = 498.38N/mm^2

The other values can be noted from Table 5,

$(P_i)_3$ is the average value of tensile strength at level 3 of factor P_i = 512.0N/mm^2,

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$(T_m)_3$ is the average value of tensile strength at level 3 of factor T_m= 513.2N/mm^2,

$(P_h)_3$is the average value of tensile strength at level 3 of factor P_h = 505.5N/mm^2,

$(v_i)_1$ is the average value of tensile strength at level 1 of factor P_i= 506.9N/mm^2, and

$(\varphi)_2$is the average value of tensile strength at level 2 of factor φ = 510.9N/mm^2

Hence,

μ_{TS} = 512.0 + 513.2 + 505.5 + 506.9 + 510.9 - (4 x 498.38) = 554.98N/mm^2

The expected tensile strength at the optimum condition is 554.98N/mm^2.

The 95% confidence interval (CI) for the expected yield from the confirmation experiment can be calculated using eq. (2) as follows:

$$CI = \left(F_\alpha(\vartheta_1, \vartheta_2)V_e\left[\left(1/n_{eff}\right) + \left(1/r\right)\right]\right)^{1/2} \quad (2)$$

Where,

n_{eff}= (N/(1+ total degree of freedom of all factors used for estimating μ)

r= sample size for the confirmation experiment, r ≠ 0.$F_\alpha(\vartheta_1, \vartheta_2)$is the variance ratio of ϑ_1 and ϑ_2 at level of significance α. The confidence level is (1-α), $\vartheta_1$is the degree of freedom of mean (equal to 1) and $\vartheta_2$is the degree of freedom for the pooled error. Variance for pooled error is V_e. The confidence interval indicates the maximum and minimum levels of the optimum performance.

Tabulated F-ratio at 95% confidence level (α = 0.05): $F_{0.05;(1,16)}$ = 4.49

n_{eff}= [27 x 5/11] = 12.27

CI = {4.49 x 0.0900[(1/12.27)+(1/5)]}^{½} = ± 0.337 (3)

Therefore, the expected tensile strength at optimum condition = 554.98 ± 0.337

i.e. 554.64<μ_{TS}<555.32

The effect of injection molding parameters on ultimate tensile strength is evaluated with the help of ANOVA with an aim to find the significant factors and their percentage contribution to ultimate tensile strength. From Table 7, it is observed that the factors: injection pressure, mould temperature, holding pressure, injection speed, and powder loading are the significant factors, which influence the ultimate tensile strength of the molded parts. The injection temperature, holding time, cooling time , interaction of injection pressure and injection temperature, and interaction of injection pressure and mould temperature are the insignificant factors therefore the pooling is needed. After pooling the contribution of injection pressure is found to be greatest at 29.23% with a confidence level of 95%, while the mould temperature is second most significant factor with 13.34% contribution at 95% confidence level. The holding pressure has a contribution of 7.47 % at 95% confidence level, the injection speed has a contribution of 3.95% at 95% confidence level, and the powder loading has a contribution of 2.45% at 95% confidence level. The interaction effect of process parameters can be observed from Fig 4 to Fig 14.

To confirm the prediction, another five samples were made at the recommended setting $(P_i)_3$, $(T_m)_3$ $(P_h)_3$, $(v_i)_1$ and $(\varphi)_2$ as shown in Table 8. The results are given in Table 9. The ultimate tensile strength obtained by processing at optimum process parameters is 550.41 N/m^2. The difference between the experimental results and predicted results is about 0.81%. The comparison between experimental and predicted results can also be observed from Fig 15.

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VI. ACKNOWLEDGEMENTS

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