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Application of design of experiments (DOE) to simulate selective laser melting process for optimum temperature distribution

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ABSTRACT
The emerging technology in manufacturing is the Rapid Prototyping, by which one can fabricate the functional testing parts within less time. Rapid Prototyping (RP) includes different techniques viz., Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), 3D Printing etc.. By the advancement of laser technology a new method called selective laser melting is evolved to fabricate metal parts directly from the metal powder. The difference between selective laser sintering(SLS) and selective laser melting(SLM) is that with SLS the powders are combined by a binding admixture, while with SLM the laser fully melts the powders, producing near full density parts in one step. Temperature distribution while fabricating parts plays a vital role both in physical properties and mechanical properties. Model simulation using Analysis packages is a new trend in research to minimize time and experimental cost. In this paper a powerful statistical tool called Design of Experiments is used to simulate the Selective Laser Melting Process to find the dependency of various parameters like Laser Power, Scan Velocity, scan interval for optimum temperature distribution.90W-7Ni-3Fe powder thermo-physical properties are used for simulation using ANSYS. Three levels for each process parameters were selected based on the literature and L9 orthogonal array design is used to investigate the most significant parameters of the process for maximum temperature distribution.

Key words: Selective Laser Melting- Simulation model- Design of Experiments- Temperature Distribution.

1. INTRODUCTION
Design of Experiments (DOE) is one of the most powerful statistical tool to investigate the optimum solutions with less effort both in time and cost. Application of this method is vast is agricultural, production quality research. Comparatively less number of applications is observed in engineering research. R.Anitha et al. [1] used taguchi technique to investigate the critical parameters influencing the quality of prototypes of Fused Deposition Modelling. H.J.Yang el al. [2] finds the shrinkage compensation of the SLS process by using the Taguchi method. K.Chockalingam et al. [3] used DOE technique to optimize the strength of parts made by Stereolithography process.Mircea Ancau and Cristian Caizar [13] used Pareto-optimal set for multicriterial optimization of rapid prototyping processes. Basic steps in Design of Experiments are as follows [12]

(a) Recognition of and statement of the problem
(b) Choice of factors, levels and ranges
(c) Selection of response variable
(d) Choice of experimental design
(e) Performing the experiments
(f) Statistical analysis of the data
(g)Conclusions and suggestions

Model simulation is a well known technique to study the behavior of physical systems without disturbing the same. D.E. Karalekas et al. [4] used photo elastic models of Stereolithography processed parts for stress analysis investigations. R.K. Chin et al.[5] proposed a thermo mechanical model for molten metal droplet solidification. Ruidi Li et al. [7] proposed a 3D transient thermal finite model to simulate the temperature distribution of Selective laser melting process. D.Q. Zhang et al. [6] used 3D finite element model to simulate select laser melting of W-Ni-Fe powders.
Simulation is imitation to the real world problem. Once the simulation model is developed which behaves as the physical model, that model can be used to study the response of the physical model for various controllable factors. Where as in Design of Experiments, most significant factor on the process can be found by doing the experiments on the physical system itself. In this paper a new approach is proposed to combine the computer simulation model and Design of Experiment to optimize the temperature distribution of Selective Laser Melting (SLM) so that merits of both the techniques are acquired in investigation.

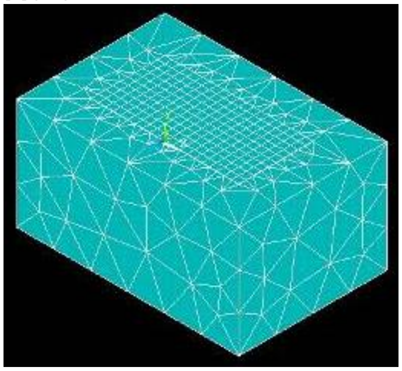

Figure 1
SLM Model used for analysis

2. FORMULATION OF HEAT TRANSFER MODEL FOR SLM
The model of SLM processing based on FE method is shown in Fig.1. The substrate is fixed on the inner of forming chamber by four symmetrical screws and is restricted to moving only in the direction of z- axis. The model consists of two different parts: (a) a metal substrate (underneath the model); (b) a powder bed (upside the model), with the dimensions of 2 x 3 x 1.5 mm and 1 x 2 x 0.05 mm. In order to obtain exact calculation as well as sufficient calculation efficiency, the substrate is meshed by solid 90 as a free grid while the powder bed is meshed by solid 70 elements with the dimension of 0.05 X 0.05 X 0.05 mm.
ANSYS 12.0 software is used for transient heat transfer analysis of the model described. The 3D heat transfer equation is [9]

Vijay et al.
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Indian Journal of Engineering, 2012, 1(1), 4-7,

$$[C_T]\{\overset{*}{T}\} + [K_T]\{T\} = \{Q\}$$ ----------- (1)

Where $C_T = \int_V \rho c[N][N]^T dV$ is the heat capacity matrix, [N] is the shape function matrix, $[K_T] = \int_V \rho c[B][B]^T dV$ is the heat conduction matrix, {T} and $\{\overset{*}{T}\}$ are, respectively, nodal temperature vector and nodal temperature rate vector, and {Q} is heat flux vector.

The assumptions used in this analysis are

- The heat convection transfer only happens between outer boundary and atmosphere
- The chemical reaction, fluid, and characteristic in the tiny melting pool was neglected
- The laser power density submits the distribution of Gaussian heat source.

Table1 Thermal properties of W-Ni-Fe metal powder

Temperature (T ^{O}K)	200	600	800	1000	2000	3500
Heat conductivity (λ W m^{-1} K^{-1})	141.9	112.18	110	103	95	83
Specific heat (C_P Jkg^{-1} K^{-1})	137.41	144.41	147.84	151.74	183.53	294.36

3. MATERIAL PROPERTIES USED FOR THE ANALYSIS

Investigations of K. Dai and L. Shaw [8] show that there is close relationship between the temperature dependent thermal physical parameters and temperature field distribution, especially heat conduction and effective thermal conductivity. There is good mutual solubility between Ni and Fe which lead to a complete solid solution. In addition, the large solubility of W in Ni and Fe made it easier to form γ- substrate phase with a relative lower melting temperature. A homogeneous alloy characterization can be found with a special W-Ni-Fe mixture powder according to W: Ni: Fe equal to 90:7:3 by weight. Using the theory of calculating parameters of mixture powder, the thermal physical parameters of composite metal powder are calculated using Eq.2 [9] and are as shown in Table 1.

$$C_P = 3R\left(1 - \frac{\theta_D{}^2}{20T^2}\right) + 2bT + 4dT^3$$ ---- (2)

Where $\theta_D{}^2$ is Debye characteristic temperature, when using C_P [J/Kg. K] and T(K) to express, Eq.2 can be rewritten as below[9]:

$$C_P = 0.1357676\times10^3\left(1 - \frac{4805}{T^2}\right) + (9.1163\times10^{-3})T + (2.313154\times10^{-9})T^3$$ ---------------- (3)

Investigations of D.Q. Zhang and Q.Z Cai, et al., [9] shows the coefficient of heat conductivity takes great effect in the forming mechanism. It can be calculated using Eq. 4[9], if there is no deformation between the metal powders with the shapes of balls:

$$\frac{k_c}{k_g} = \left(1-\sqrt{1-\phi}\right)\left(1+\frac{\phi_{kr}}{k_g}\right) + \sqrt{1-\phi}\times\left(\frac{2}{1-\frac{k_g}{k_s}}\left(\frac{1}{1-\frac{k_g}{k_s}}\ln\left(\frac{k_s}{k_g}\right)-1\right)+\frac{k_r}{k_g}\right)$$ ------------- (4)

Where k_g and k_s stands for heat conductivity of the environment gas and solid material respectively. Φ is the material porosity about 0.477. k_r is the heat conductivity coefficient introduced by radiation of the metal powder

3.1. Moving Gaussian heat source model

In SLM technique, the laser energy can be regarded as the form of heat flow density imported into the powder bed which obeys the Gaussian heat source distribution [9]

$$q = \frac{2AP}{\pi\omega^2}\exp\left(-\frac{2r^2}{\omega^2}\right)$$ --------------- (5)

Where ω is equivalent radius of laser beam, the distance is from the center of the laser beam area to the point with heat flow density mitigated to the $1/e^2$. A is powder bed absorptivity to laser beam; P is the laser power, the distance from powder bed to the center of the laser beam area can be written as [9]

$$r^2 = (x-x_0)^2 + (z-z_0-vt)^2$$ ------- (6)

3.2. Treatment of the boundary conditions and initial conditions

For the domain D, the initial condition is

$$T(x,y,z,0) = T_0 \quad for(x,y,z)\in D$$

The natural boundary condition can be defined by

$$\lambda_e\frac{\partial T}{\partial n} - q + h(T-T_0) + \sigma\varepsilon(T^4 - T_0{}^4) = 0$$

On the boundary, S represents those surfaces that are subject to radiation and convection and impose heat fluxes. Where λ_e is thermal conductivity normal to S; h is heat transfer coefficient for convection; σ is Stefan-Boltzmann constant for radiation; ε is emissivity and T_0 is the ambient temperature.

4. DESIGN OF EXPERIMENTS TO SLM

The different controllable factors of SLM process are velocity of the laser beam v (mm/s), power used for laser beam P (W), Scanning interval S (mm), Preheat temperature T_p, Ambient temperature T_0 etc., According to the investigations of D.Q.Zhang et al., [9] and LONG Ri-sheng et al., [11] the temperature distribution is mostly influenced by Power, velocity, scanning interval and ambient temperature. Three levels for each factor are selected as in Table 2, in which the ranges are selected according to the literature.

Table 2 levels of different factors in SLM

Factors	Levels 1	2	3
A. Power(W)	70	85	100
B. Velocity(mm/s)	20	80	140
C. Scanning Interval (mm)	0.05	0.075	0.1
D. Pre heat Temp. (^{0}C)	100	150	200

Table 3 L9 orthogonal array

Std	Run	Fact1 A.A	Fact2 B.B	Fact3 C.C	Fact4 D.D
5	1	A2	B2	C3	D1
1	2	A1	B1	C1	D1
4	3	A2	B1	C2	D3
3	4	A1	B3	C3	D3
6	5	A2	B3	C1	D2
9	6	A3	B3	C2	D1
8	7	A3	B2	C1	D3
7	8	A3	B1	C3	D2
2	9	A1	B2	C2	D2

Table 4 Repose for L9 orthogonal array

Run	Temp. Difference ^{0}C	Temp. Gradient ^{0}C/mm
1	699	6000
2	621	11000
3	492	4500
4	577	9000
5	818	10000
6	567	4100
7	912	8000
8	877	8000
9	393	3600

The objective function of the model is to maximize the temperature distribution of the temperature in SLM process. This can be described by the temperature gradient of the moving heat source in the plane from the point of application of the heat. If the temperature gradient is more, means that isothermal curves will move farther from the source point. With four factors

and three levels of full factorial design includes 64 runs which is time taking and expensive in practical. Taguchi's orthogonal array of L9 series provides more accurate assessment for finding the most effective main factors on the response with less number of runs. The experimental design for L9 orthogonal array as shown in Table 3 is used for simulation. In the above Table 2 indicates low level, 2 for medium and 3 for high levels of the factors. Random numbers for the simulation run is generated through the statistical technique and is implemented for the runs. In the first run 85 W of power, velocity of laser beam as 80 m/s, scan interval of 0.1 mm and pre heat temperature of 100^{0}C is used as the input variables with material properties and element type unchanged in the simulation using ANSY transient heat transfer. Simulation is carried out for two turns of deposition. The response for each of the simulation is temperature distribution in terms of temperature difference and temperature gradient and is shown in Table 4.

5. RESULTS AND DISCUSSION

APDL programme is developed to investigate the temperature distribution and gradient for all the runs. Fig. 2 shows the temperature distribution of run 6 in which power of laser is 100 W, scan velocity of 140 mm/s, scan interval of 0.075 mm and pre heat temperature of 100^{0}C, at the time of laser beam reaches the end of one complete turn. Fig 3(a), (b), (c) shows the temperature variation of first row middle node while the laser beam moves for one complete turn. Here the three graphs are drawn based on the scan velocity. Fig 3(a), (b) and (c) are for beam velocities of 20 mm/s, 80 mm/s and 140 mm/s respectively.

For knowing the most influencing factors for the optimum temperature distribution, statistical technique called Analysis of Variance (ANOVA) is used which is a tool in statistical software Design Expert (DX-8.0). Result analysis is given in the Table 5, from this power of the laser beam (A) and scan interval (C) are identified as most significant factors for the optimum response. The significant factors can also be identified using half normal graph as shown in Fig 4. In the above graph factors A and C are away from the normal line which means that a small variation of these factors will influence the

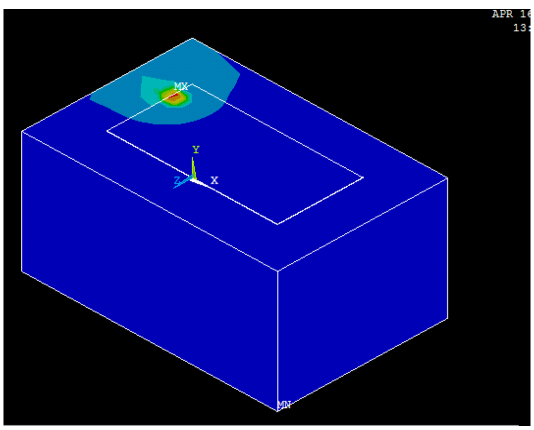

Figure 2
Temperature distribution of run 6

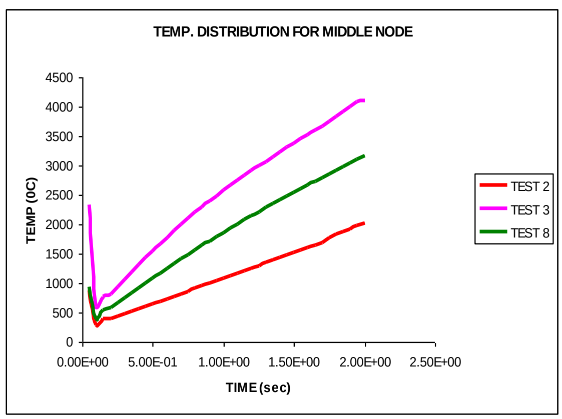

Figure 3(a)
Temp. variation of middle node for run 2,3 and 8

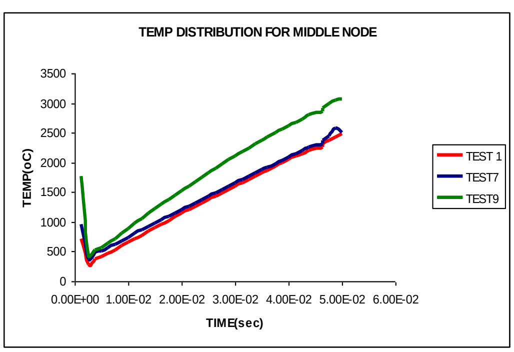

Figure 3(b)
Temp. variation of middle node for run 1,7 and 9

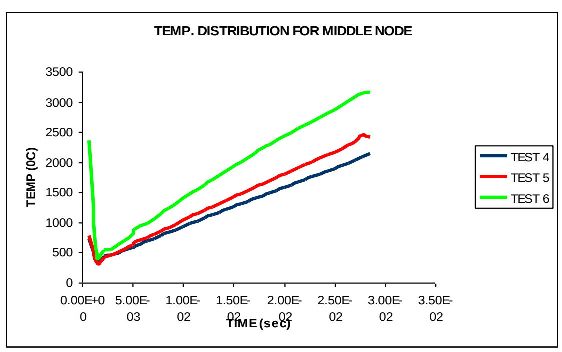

Figure 3(c)
Temp. variation of middle node for run 4,5 and 6

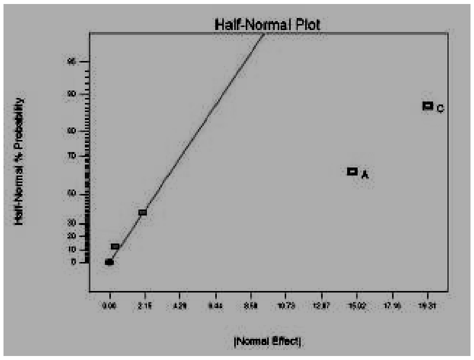

Figure 4
Half normal plot for significant main effects

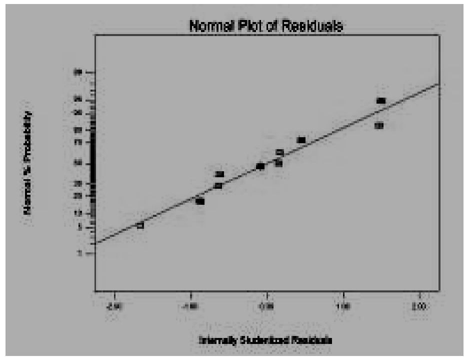

Figure 5
Normal plot of residuals for all the runs

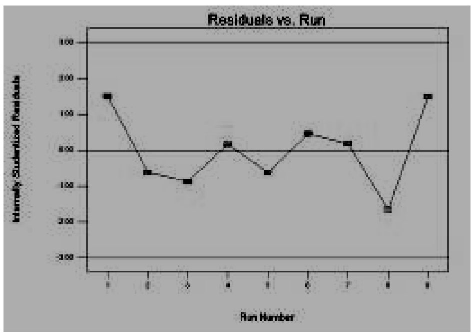

Figure 6
Checking the scatterings of residuals

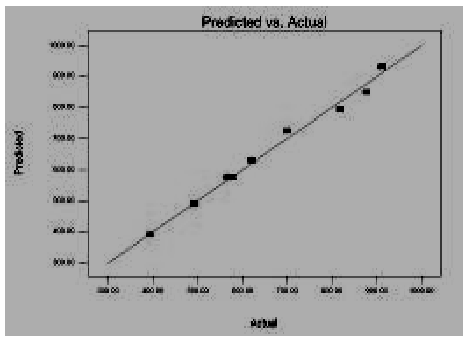

Figure 7
Predicted vs actual values of the response model

response more. The outcome of the Design of experiments is the response equation which is in terms of factors with its corresponding coefficients. From this response equation one can estimate the predicted values for any level of factors within the range. In finalizing the most significant Design Expert software is performing other tests like residual test, Box-Cox plot for power transformations, variation of one factor at a time etc., Fig. 5 shows the normality of the residual of the model, which shows that the residual is propagating on either sides of the normal value of the model. Fig. 6 shows the graph of residual versus run, the residuals are scattered about the exact value of the model, which is a necessary condition for the runs in DOE. Fig. 7 show the graph of predicted versus actual response of the model. The model selected for analyzing the data using Design Expert is $\log_{10}$ for accommodating the large of range of data. The graph shows that the predicted values are very close to the actual values.

6. CONCLUSION

A powerful statistical tool called Design of Experiments is used to investigate the significant factors for Sintered Laser Melting process. Simulation of the process is carried out using FEA software called ANSYS and the results were analyzed using Design Expert. From the analysis it is observed that for optimum temperature distribution, power of the laser (A) and scanning interval (B) are most significant factors. Care must be taken while changing these variables because a small variation of in these factors level will affect the response more.

Table 5 ANOVA for L9 array

ANOVA for selected factorial model						
Analysis of variance table [Classical sum of squares - Type II]						
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	0.621842	4	0.15546	150.6594	0.0001	
A-POWER	0.23052	2	0.11526	111.7006	0.0003	significance
C-SCAN INTERVAL	0.391321	2	0.195661	189.6182	0.0001	
Residual	0.004127	4	0.001032			
Cor Total	0.625969	8				

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Vijay et al.
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