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Optimization of Selective Laser Melting by Evaluation Method of Multiple Quality Characteristics

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Abstract. Article describes the adoption of the Taguchi method in selective laser melting process of sector of combustion chamber by numerical and natural experiments for achieving minimum temperature deformation. The aim was to produce a quality part with minimum amount of numeric experiments. For the study, the following optimization parameters (independent factors) were chosen: the laser beam power and velocity; two factors for compensating the effect of the residual thermal stresses: the scale factor of the preliminary correction of the part geometry and the number of additional reinforcing elements. We used an orthogonal plan of 9 experiments with a factor variation at three levels (L9). As quality criterias, the values of distortions for 9 zones of the combustion chamber and the maximum strength of the material of the chamber were chosen. Since the quality parameters are multidirectional, a grey relational analysis was used to solve the optimization problem for multiple quality parameters. As a result, according to the parameters obtained, the combustion chamber segments of the gas turbine engine were manufactured.

1. Introduction

At the present time additive production methods are becoming increasingly widespread in the aerospace industry. Selective laser melting (SLM) makes it possible to manufacture parts of complex shape, but in the process of selective laser melting the temperature changes and distribution of temperature loads, which leads to the appearance of residual stresses [1, 2]. In addition, as a result of this thermal history, an anisotropic microstructure is formed. The final properties of the material (e.g. endurance strength and tensile strength) are directly related to the microstructural features of the part, and therefore the presence of residual stresses is unfavorable [1, 3]. The effect of the melting direction on the residual stresses was studied in [4, 5]. As a result of residual stresses from thermal loads, the laser induced synthesis of thin-walled parts generates significant deformations resulting in defective parts. In this respect, the actual task is to develop compensation methods for the residual stresses.

The compensation methods may be conditionally divided into 4 groups:

1. Optimization and correction of the melting process's operating parameters, including the laser power, the laser beam velocity, the beam width, scanning strategy;
2. Optimization of heat removal into the base platform through a substrate;
3. Topological optimization of the structure by adding removable technological elements such as supports to increase the rigidity and to prevent distortion from the thermal stresses effect;
4. Compensation of residual stress effect by introducing the pre-correction of part geometry.

The application of the first method is complicated by the fact that it is not always possible to select the sintering mode quickly, as it is necessary to take into account not only the properties of the basic material, but also part's design features. The second method is carried out by selecting the quantity, the cross-section geometry and the location of the heat sink. The latter two methods are particularly effective in growing thin-walled parts, where ensuring rigidity is most important. The preliminary correction can be performed by initial estimating the resultant deformations. In that case part configuration changes by inverting the distortion values multiplied by the configuration correction degree.

2. Materials, Methods and Equipment

The SLM build-up of the combustion chamber segments from the nickel-chromium metal-powder composition was performed on a selective laser melting machine SLM 280HL.

The measurements were carried out on a coordinate measuring machine DEA GLOBAL Performance. Numerical modeling of the SLM process was performed using the Simufact Additive© v1 software (trial ver. [6])

For SLM build-up, a metal powder with a fraction size of 40 μm of VV751P mark, the chemical composition of which is given in Table 1.

Table 1. Chemical composition of metal powder VV751P

Fe	*C*	Si	*Mn*	*Ni*	*S*	P	*Cr*	*Ce*	*Mo*	*W*	*V*	*Co*	*Nb*	*Ti*	*Al*	*B*	*Pb*	*Mg*	*La*
up to 1	0.04 – 0.08	up to 0.3	up to 0.3	50.09 – 50.86	up to 0.009	up to 0.015	10 -12	up to 0.01	4 - 5	2.5 - 3.5	0.4 – 0.8	14 - 16	3 – 3.5	2.5 – 3.1	3.7 – 4.2	up to 0.015	up to 0.07	up to 0.01	up to 0.02

The detailed experiment of a part's production by SLM method can be found in the works [5, 7].

For the study, the following optimization parameters (independent factors) were chosen: P is the laser power, v is the scanning velocity; two factors for compensation of residual thermal stresses, M is the scale factor for preliminary correction of the part configuration and t is the indicator for the introduction of additional stiffeners ($t = 0$ means stiffeners are absent, $t = 1$ – lengthwise stiffeners are introduced, $t = 2$ – lengthwise and transverse stiffeners are introduced). As dependent factors (quality parameters), the values of maximum and average deformations from the residual stresses effect were selected in 9 surface areas of the combustion chamber segment. The second quality parameter is a value of the ultimate strength for the melting conditions corresponding to the experiments. The values of distortion for various matched melting conditions were obtained by numerical methods using a verified experimental model.

To determine the tensile strength σ depending on the operating parameters of laser melting we used a second-order regression model (1).

$$\overline{\sigma} = 0,25 + 1,0627\overline{v} + 0,1532\,\overline{p} + 1,5324\,\frac{\overline{p}}{\overline{v}} - 1,3121\overline{v}^2 - 1,294\left(\frac{\overline{p}}{\overline{v}}\right)^2, \qquad (1)$$

Where normalized parameters are written as: $\overline{\sigma} = \dfrac{\sigma - 891}{241}, \overline{v} = \dfrac{v - 710}{100}, \overline{\mathrm{p}} = \dfrac{P - 225}{100}$

Since it was assumed that the main results of the experiments will be obtained by numerical methods, a full-scale experiment on combustion chamber segment growing was conducted to verify the numerical model of the SLM process and to estimate the calculation error. It was found that the calculated and measured distortion values have a good correlation. The calculated distortion values were further used as process quality parameters to estimate the distortion values on various melting modes.

3. Taguchi Quality Method

The key principle of Taguchi quality measurement methods is minimization of changeability (variability) in the technology of part manufacturing in response to noise factors and maximization of variability in response to control factors. The noise factors *N* are those that are not under the control of the technology, or are not pertain to the optimization problem. Signal factors *S* are those factors that are established or controlled by the technological process for a specific optimization problem. The goal of the quality improvement can be stated as an attempt to maximize the signal-to-noise ratio (S/N) for the corresponding product. When the task is nominal-is-better, it means to minimize the development of some undesirable characteristics of the product. In our case such characteristics are deformations caused by residual stresses. The S/N ratio should be calculated as follows [8]:

$$\xi = -10\log\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \qquad (2)$$

where y_i is the observed value in the experiment, n is the total number of experiments.

For our research we chose orthogonal array L9 (4×3) according to Taguchi method [8]), which represented 9 sets of experiments and contained 4 three-level factors (Table 2).

Table 2. Quality parameter values

№	P, W	v, mm/s	M	t	Maximum distortion value on areas of combustion chamber segments, mm									σ, MPa
					A1	A2	A3	A4	A5	A6	A7	A8	A9	
1	290	700	-0,80	0	3	2,80	1,80	2,80	1,80	1,80	4,00	1,8	1,8	1020
2	290	760	-1,00	1	0,317	0,81	1,07	0,51	0,39	0,39	0,34	0,57	0,65	1120
3	360	760	-0,80	2	1,2	1,2	1,2	1,4	1,4	1,4	1,2	1,2	1,4	1053
4	325	700	-1,00	2	0,4	0,60	0,80	0,30	0,30	0,30	0,60	0,6	0,6	966
5	360	800	-1,00	0	1	1,37	1,42	0,86	0,54	0,54	1,41	1,08	0,9	1025
6	360	700	-1,20	1	0,64	1,13	1,44	0,78	0,59	0,59	0,54	1,024	0,88	864
7	325	760	-1,20	0	1,2	1,39	1,44	0,97	0,67	0,67	1,67	0,32	0,99	1107
8	290	800	-1,20	2	0,68	0,87	1,17	0,58	0,44	0,48	0,46	0,704	0,605	1046
9	325	800	-0,80	1	1,6	1,00	1,60	1,60	1,20	1,60	1,00	1,6	1,2	1054

4. Main Effect Analysis

For main effect analysis we used the following dependence:

$$\Delta F = \max(\bar{F}_1, \bar{F}_2, ..., \bar{F}_n) - \min(\bar{F}_1, \bar{F}_2, ..., \bar{F}_n), \quad \bar{F}_i = \frac{1}{m}\sum_{j=1}^{m} y_{ij} \qquad (3)$$

where $\bar{F}$ is the mean S/N ratio of the i-th level of factor F, m is the number of the i-th level of each factor, y_{ij} is the jth S/N ratio of the i-th level, ΔF is the value of the main effects of factor F, and n is the number of the level of each factor. The higher a factor's main effect value, the greater this factor's impact on the system will be.

In accordance with factor's main effect value where $\Delta F = 1,62375$ is for laser out power (P), $\Delta F = 0,43756$ is for scanning velocity (v), $\Delta F = 7,78723$ is for configuration correction scale factor

(M) and $\Delta F = 5,08169$ is for additional stiffeners (t) taking into account the grade of factor's impact on the quality, factors may be ranged in the following manner: $1-M,\ 2-t,\ 3-p,\ 4-\nu$

5. Analysis of Variance (ANOVA)

ANOVA helps to identify the effects of the individual factors on distortion value as quality characteristics. ANOVA results are presented in Table 3. Scale factor of configuration correction is excluded due to its low integrity according to parameters value F and p based on preliminary analysis. The lower F value and the higher p value, the more adequate is the assessment of the factor's effect, estimated by the *SS* deviation value. *SS* factors are ranged by value in the descending order: $1-t,\ 2-P,\ 3-\nu$.

Scale factor of configuration correction M due to its low integrity according to F criterion did not was not analysed.

Table 3. ANOVA results without the effect of corrective scale factor

	SS	df	MS	F	p
1 – Laser power	4.42766	2	2.21383	0.046462	0.955601
2 – Velocity	0.35226	2	0.17613	0.003697	0.996317
4 – Stiffness factor	40.09485	2	20.04742	0.420740	0.703858
Residual stresses	95.29594	2	47.64797		

The use of the F test compensates for the defects of the Taguchi method experiments, such as failure to identify the effects that the different experiments may have on quality characteristics or the level of experimental errors.

Figure 1 shows a graph of the signal-to-noise ratios of quality parameters in orthogonal experiment L9 according to Taguchi.

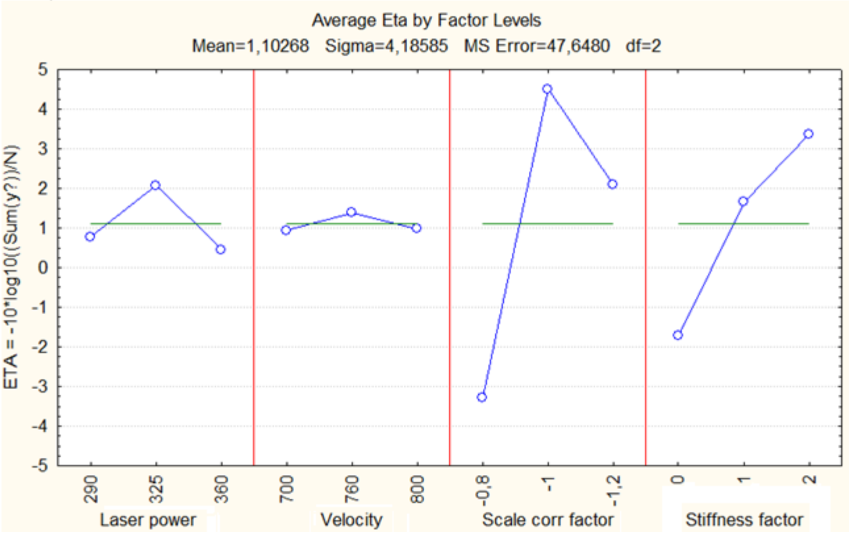

Figure 1. Average η depending on Control Factor Levels

Response graph (Figure 1) of average quality parameter η shows that the optimal operating SLM conditions of combustion chamber segment corresponds to the parameter value: laser power – 325 W, scanning velocity – 760mm/min, scale factor value of geometry correction -1 and introduction of additional stiffing elements relevant to maximum level.

6. Grey Relational Analysis

For a high quality part an average (and maximum) values of distortion must be minimized and the ultimate tensile strength values must be at maximum. As in this case Taguchi's lower-the-better analysis for quality characteristics is inapplicable due to their diversity, we used grey relational analysis. Grey relational analysis is a method of measurement in the grey system theory, which analyzes the degree and the level of the ratio of heterogeneous parameters for their discrete sequence.

The initial experimental data were first normalized in the range from 0 to 1 in accordance with the principle "the smaller-is-better" for distortion value using the following function:

$$x_{ij} = \frac{y_{ij} - \min_j y_{ij}}{\max_j y_{ij} - \min_j y_{ij}}, \qquad (4)$$

$y_{ij} = \max_n y_{ij}^n$ is the most negative quality characteristic (distortion value) among $n = 1....9$ concerned areas of developed combustion chamber. The best normalized result corresponds the value 1.

For maximum strength which is characterized by the-higher-the-better normalization was carried out using the following dependence:

$$x_{ij} = \frac{\max_j y_{ij} - y_{ij}}{\max_j y_{ij} - \min_j y_{ij}}, \qquad (5)$$

where y_{ij} is the value of maximum strength for j-th experiment, calculated using the dependence (1).

Grey relational coefficient ξ_{ij}, which is calculated to define ratio between ideal and factual experiment results may be as follows [8]:

$$\xi_{ij} = \frac{\min_i \min_j |x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|}{|x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|}, \qquad (6)$$

where

x_i^0 is the ideal result (i.e. the best normalized result =1) for i - quality characteristics, $\zeta = [0,1]$ is the distinguishing coefficient, which target is to weaken the effect of $\max_i \max_j |x_i^0 - x_{ij}|$, when it becomes too high and therefore increases the value difference of the grey relational coefficient. In general, its value is taken to be 0.5 if all process parameters have equal weight.

Table 4 presents the grey relational coefficients for every experiment of orthogonal array L9. The weighting method is then used to integrate the obtained values of the grey relational coefficients ξ_{ij} for each experiment into an integrated relational evaluation. The overall assessment of multiple quality characteristics is based on an integrated relational evaluation, which is determined by the following dependence:

$$\gamma_j = \sum_{i=1}^{m} \frac{l_i}{\sum_{i=1}^{m} l_i} \xi_{ij} , \qquad (7)$$

where l_i is the value level of i -h quality characteristic.

The resulting integrated relational estimates are shown in Table 4. The higher the integrated relational rating, the better the result of the experiment, the closer it is to the ideally normalized value.

The effect of each parameter of manufacturing process on the integrated relational evaluation at different parameter levels is taken into account separately, whereas the experiment plan is orthogonal.

In Table 4 y_1, y_2 are the maximum values for every experiment according to an average and maximum distortion, taken in 9 areas, y_3 is the value of maximum strength, x_1, x_2, x_3 are normalized by dependences (4) and (5) factors.

Table 4. Results of grey relational analysis

	y_1	y_2	y_3	x_1	x_2	x_3	ξ_1	ξ_2	ξ_3	γ
1	2,20	4	1020	0	0	0,6078	0,3333	0,3333	0,5604	0,44685
2	0,84	1,067	1120	0,7533	0,9166	1	0,6696	0,857	1	0,90039
…										
8	0,95	1,17	1046	0,6972	0,8844	0,7098	0,6228	0,8122	0,6328	0,69409
9	1,20	1,6	1054	0,5556	0,75	0,7412	0,5294	0,6667	0,6589	0,642205

The values of the relational estimates ξ_i were calculated from the dependence (6) on the vector of the desired normalized quality parameters $x_i^0 = (1,1,1)$, which corresponds to the maximum quality parameters obtained in all numerical experiments. The integral relational estimation γ was determined by the formula (7), while for the maximum value of the average distortion value in 9 areas (x_{1j}) it was accepted that $l_1 = 30\%$, for the greatest distortion value in 9 areas (x_{2j}) $l_2 = 70\%$, for the ultimate strength limit (x_{3j})- $l_3 = 100\%$.

Based on the calculated values γ , it is seen that the maximum value of the integral relational estimate (0.90039) has a second experiment, Table 4. These values of the factors best correspond to the vector of desirability of the quality parameters. According to the combination of the both analysis's results, and in accordance with the degree of factor values effect on the quality characteristics for growing of the combustion chamber segment, the following modes were adopted: laser power - 290 W, scanning velocity - 760 mm / min, additional stiffness elements -2 (maximum level). The segment of the grown combustion chamber is shown in Figure 2.

Figure 2. Manufactured combustion chamber segment.

7. Conclusion

This research is focused on the evaluating the process of selective laser melting of thin-walled not rigid parts prone to thermal warpage. This study combines the Taguchi method and orthogonal experiment plan consisting of 9 experiments to evaluate part quality. The Taguchi method was applied to optimize such manufacturing factors as radiation power, hatching speed, scale factor of geometry correction, adding of additional stiffness elements. Based on the experiment analysis results, we found the optimal values of the laser melting modes of the combustion chamber segment of a gas turbine engine from a heat-resistant nickel-chromium powder. These technological factors were ranged according to the degree of their impact on quality parameters. It is necessary to note that the Taguchi method is applicable mostly to optimize the single quality characteristic as distortion values from residual stresses during SLM process. It does not provide an agreed solution for the case when it is necessary to use multiple quality characteristics, such as distortion value and mechanical features. For this case grey relational analysis was adopted. The results of this method applying at the same experiment plan as the Taguchi method were different from the latter, as it takes into account more characteristics, in particular the maximum strength. The degree of consistency of multiple quality characteristics was taken into account based on the adopted desirability vector and the coefficients of impact and the level of accepted significance levels of the factors.

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