ИЗЫСКАНИЕ, ПРОЕКТИРОВАНИЕ, СТРОИТЕЛЬСТВО И МОНТАЖ ТЕХНОЛОГИЧЕСКОГО ОБОРУДОВАНИЯ ОБЪЕКТОВ АТОМНОЙ ОТРАСЛИ

УДК 621.91

ПРИМЕНЕНИЕ D-ОПТИМАЛЬНЫХ ПЛАНОВ ЭКСПЕРИМЕНТА ДЛЯ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ ПРОЦЕССА ЛАЗЕРНОЙ НАПЛАВКИ МЕТАЛЛИЧЕСКОГО ПОРОШКА

© 2017 А. Марко[*], Б. Граф[*], С. Гоок[*], М. Ретмайер[*,]**

[*] *Общество Фраунгофера, Институт производственных систем и технологий конструирования ИПК, Берлин, Германия*

[**] *Федеральное ведомство по исследованию и испытаниям материалов БАМ, Берлин, Германия*

Процесс лазерной наплавки металлического порошка Laser Metal Deposition (LMD) находит все более широкое применение в энергетическом машиностроении. В качестве наиболее актуальных приложений данной технологии можно выделить нанесение покрытий с заданными свойствами на исходную деталь, а также восстановление изношенной или поврежденной геометрии изделий машиностроительного производства, например лопаток турбин. Для достижения наибольшей эффективности и производительности процесса LMD необходимо привлечение наиболее полной информации о степени влияния основных параметров процесса, таких как мощность лазерного излучения, скорость процесса и расход порошка на конечный результат наплавки, а именно на ширину и высоту валиков наплавки. Подобные задачи оптимизации могут эффективно решаться с использованием методов статистического планирования эксперимента, которые в зависимости от выбранной стратегии оптимизации могут быть довольно трудоемкими. По соображениям экономии времени на проведение исследования актуальным является ограничение числа отдельных точек эксперимента. Введение D-оптимального плана позволяет извлечь максимальное количество информации о зависимой переменной в экспериментальной области, используя меньшее количество точек эксперимента по сравнению с полнофакторным планом. Согласно литературным данным (Subramaniam et al., 1999), эффективность подобных планов эксперимента показана при оптимизации сварочных процессов [8]. Возможность применения D-оптимального плана эксперимента для оптимизации процесса лазерной наплавки не была исследована до настоящего времени.

В настоящей работе исследуется применимость D-оптимального плана эксперимента для процесса LMD.

Титановый сплав Ti6Al4 использован в качестве материала субстрата и порошка для наплавки в ходе проведения экспериментов. Результаты D-оптимального плана сравнены с результатами полнофакторного плана испытаний. Продемонстрировано, что D-оптимальный план и полнофакторный эксперимент обеспечивают сопоставимые результаты. Однако, процедура эксперимента выполненная в соответствии с D-оптимальны планом эксперимента реализуется с экономией времени порядка 80%.

Ключевые слова: аддитивные технологии, планирование эксперимента, лазерная наплавка, параметры наплавки, восстановление поверхностей, ремонтная сварка.

Поступила в редакцию: 11.09.2017

1. Motivation / State of the Art

Primarily developed for coating, laser metal deposition (LMD)is applied for additive manufacturing and repair welding today as well. The possibilities of the process are manysided. Nevertheless, the requirement is always a comprehensive process understanding. An opportunity to generate process knowledge offers statistical test planning. A huge number of test plans are available. The D-optimum experimental design is characterized by an extraordinarily high flexibility. In this context, special mention should be made of the manual selection of the test points. Furthermore, according to the literature (Subramaniam et al., 1999) the application of this kind of test plans is recommended for welding processes [8]. The application for laser metal deposition has not been exercised yet. For LMD, central compound test plans or Taguchi plans are often used.

1.1. Laser metal deposition

In the process of deposition welding, an additional material is deposited on a locally restricted surface during the procedure. For laser metal deposit a laser is used as heat source. A focused laser creates a molten pool. At the same time filler material is supplied to the molten pool and is fused. After cooling time, the filler material adheres on the work piece. Inert gases like argon and helium serve as carrier gas and prevent oxidation of the materials. Frequently, an additional shielding gas is implemented to enhance the oxidation-restraining effect. Powder as filler material is supplied to the process through a nozzle. The duct of the nozzle is linear. Welding beads are formed and from these coatings are constructed. Typical dimensions of the welding beads are heights between 0.1 mm and 2 mm and widths from 0.2 mm to 6 mm.

Crucial aspects for track geometry are the factors laser power, welding velocity, powder mass flow and spot diameter (DVS - Deutscher Verband für Schweißen und verwandte Verfahren e.V., 2011) [3].

NOMENCLATURE

P	laser power	Watt
d	laser spot diameter	mm
v	welding velocity	mm / min
$\dot{m}$	powder mass flow	g / min
w	track width	mm
b	track height	mm

An important benefit of the process is the low heat input. For this reason, the materials are subjected to a low thermal and subsequently mechanical stress. Moreover, high precision of the material application as well as a good control and automation are beneficial. A wide application field arises due to these advantages. Therefore, the process is often used for the repair of cost-intensive components like sintered tools (Capello, Colombo, & Previtali, 2005) [2] or vanadium carbide tools (Leunda, Soriano, Sanz, & Navas, 2011) [5]. Increasingly engine and turbine parts are repaired using laser metal deposition.

1.2. Design of experiments

Design of experiments contains a number of different test plans and evaluation methods. The aim is to identify relations between input value and target figure. The choice of the best experimental design is made with regards to the best possible ratio between effort and information yield. That is why full and fractional factorial test plans as well as central compound experiment designs are used in many cases. Table 1 illustrates this fact.

Sun (Sun & Hao, 2012) uses a central composite experimental design in his work to investigate on the influence of laser power, welding velocity and powder mass flow on track geometry [9]. Furthermore, he considers the degree of mixing. As filler material Ti6Al4V powder and as heat source a Nd:YAG laser is used. The results show that laser power exerts the strongest influence on the track width. Weld velocity and powder mass flow only slightly affect the track width. Significant factors for the track height are weld velocity and powder mass flow.

Graf (Graf et al., 2013) uses a full factorial test plan to consider the relations on the dimensions of the welding bead [4]. Laser power, welding velocity, powder mass flow and spot diameter are varied with two steps. As filler material nickel based super alloy René 80 is used. The results also demonstrated the main influence on the track width by laser power. The track height is significantly shaped by weld velocity and powder mass flow.

Table 1. Examples of design of experiments for LMD

	Author	material	varied process parameters	test plan
(Sun & Hao, 2012) [9]	Y. Sun, M. Hao	Ti6Al4V	P; v; ṁ	central compound design
(Graf, Ammer, Gumenyuk, & Rethmeier, 2013) [4]	B. Graf, S. Ammer, A. Gumenyuk, M. Rethmeier	nickel alloy	P; d; v; ṁ	central compound design
(Narva, Marants, & Sentyurina, 2014) [6]	V. K. Narva, A. V. Marants und Z. A. Sentyurina	Ti-carbid-powder	P; v; ṁ	full factorial test plan
(Paul et al., 2007) [7]	C. P. Paul, P. Ganesh, S. K. Mishra, P. Bhargava, J. Negi und A. K. Nath	Inconel 625	P; v; ṁ	Taguchi design

As shown by the listing in table 1, up to now there are no investigations on the application of D-optimum test plans for laser metal deposition. This is presumably due to the fact that such test plans include comparably complex experimental designs. The creation of these plans is only possible with suitable arithmetic algorithms. Nowadays, a huge number of different statistics software systems are available. The advantages of these kind of test plans lie within their flexibility. Thus, the number of steps from each investigated factor can be freely chosen. Additionally, the step distances must not be kept equidistant. The distribution of the test points can occur arbitrarily in the test space. However, the essential advantage lies in the fact that certain factor combinations can be excluded. This is especially helpful in cases where some settings are practically impossible, for example, if the factor combination guarantees no regular coating. The unessential points can be excluded manually or on the basis of restrictions.

D-optimum test plans are iterative generated test plans. Often the D-criterion is used. In this manner a global minimization of the scattering behavior of the random sample regression coefficients is reached. The D-criterion is defined as follows(Arellano-Garcia, Schöneberger, & Körkel, 2007) [1]:

$$\Phi\,(\mathrm{C}) = \frac{1}{\mathrm{n}}\det(\mathrm{C})^{\frac{1}{\mathrm{n}}} \qquad (1\text{-}1)$$

Φ : Determinant
C : covariance matrix
n: dimension

Nevertheless, this equation is exclusively valid with a regular covariance matrix. In case of a non-regular matrix, a projection matrix can be utilized:

$$\Phi\ (\mathrm{C}) = \frac{1}{\mathrm{n}}\det(K^T \mathrm{CK})^{\frac{1}{\mathrm{n}}} \tag{1-2}$$

K: projection matrix
K^T: transpose projection matrix

With D-optimum test plans the quantity of the test points is variable. Nevertheless, it is depending on the amount of the coefficients in the expected mathematical model of the effect function (K_p). Thus it applies:

Test points > 1.5 x (Number of coefficients K_p in the mathematical model) (1-3)

The quantity of the coefficients K_p can also be determined mathematically. So it is relevant whether a linear or a square approach is the basis of the experiments. In this work, a square approach is assumed:

$$\mathrm{K_p} = \frac{(\mathrm{n}+1)\cdot(\mathrm{n}+2)}{2} \tag{1-4}$$

2. Experimental

2.1. *Laser metal deposition and materials*

A TRUMPF TruDisk 2.0 kW Nb:Yag laser is utilized for the experiments of this work. A 5-axis arrangement is used for movement of the powder nozzle. A 3-ray nozzle introduces the filler material in the melt pool. As a carrier gas helium is used. In addition, helium and argon are applied as protective gases.

The substrates as well as the powder are titanium alloy Ti-6Al-4V. The chemical composition is referred in Table 2. The powder particle size amounts45µm – 100µm.

Table 2. Chemical composition Ti-6Al-4V, manufacturer specification in wt.-%

Al	V	O	N	C	H	Fe	Ti
6.28	3.89	0.11	0.004	0.005	0.002	0.18	rest

2.2. *Design of experiments, welding parameters and responses*

As input variables, the parameters laser power, spot diameters, weld velocity and powder mass flow are selected. The choice occurred on basis of past experience. The factor variation is shown inTable3.

Table 3. Factor variation

Factor steps	P in W	d in mm	v in mm/min	ṁ in g/min
1	100	0.6	200	0.35
2	500	1	700	1.4
3	1000	1.4	1200	2.1
4	1500	1.8	1600	2.8
5	2000	2.2	2000	3.5

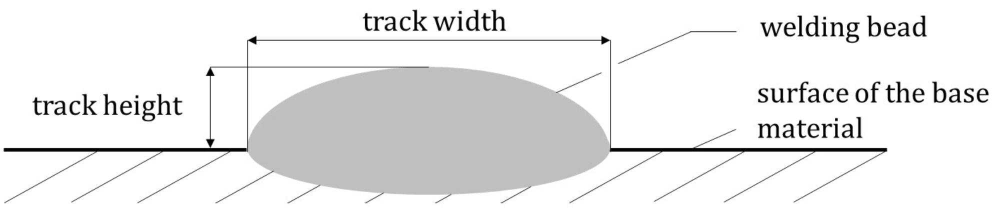

Figure 1. Target sizes

As target sizes track geometry of a welding bead was determined. Therefore, track width and track height are measured. Figure 1 shows these measured values.

According to formula 1-3, the D-optimum test plan must contain at least 21 test points. To be able to value the informative capability, in this work D-optimal test plans with 25, 50 and 100 test points are set up and evaluated. The choice of the test points occurred under the application of a statistics software. The considered D-optimum test plans are a subset of a full factorial test plan under application of restrictions. Thus, it can be made sure that only test points are included which are technically feasible. As example, with too low energy per unit length a deposit is not possible. Combinations of factor settings are used for restrictions. These can be attributed to physical dimensions: energy per unit length, surface energy and mass being melted. Limit values were defined with help of previous experiences.

Consequently, the following three restrictions arise.

Energy input per unit length

$$\frac{\text{laser power P}}{\text{weld velocity}} > 18\ \frac{\text{W}}{\text{mm}}$$

Surface Energy

$$\frac{\text{laser power P}}{\text{spot diameter d}} > 500\ \frac{\text{W}}{\text{mm}}$$

Mass is being melted

$$\frac{\text{laser power P}}{\text{powder mass flow } \dot{m}} > 418.4\ \frac{\text{J}}{\text{g}}$$

The results of the particular D-optimum test plans are compared to a 5^4 full factorial test plan. For evaluation, restrictions were also applied. In this way, the amount of test points could be reduced from 625 to 310.

3. Results

In this section, the results of the respective test plans are described. First the full factorial test plan is discussed in detail. It is used as a basis for evaluation of the D-optimum plan in order to check uncovered effects due to regression function and analysis of variance (ANOVA) and check plausibility.

3.1. Full factorial test plan

3.1.1. Track width

Graphic representation of the regression function is shown in figure 2. Matching results of the ANOVA can be taken from table 4.

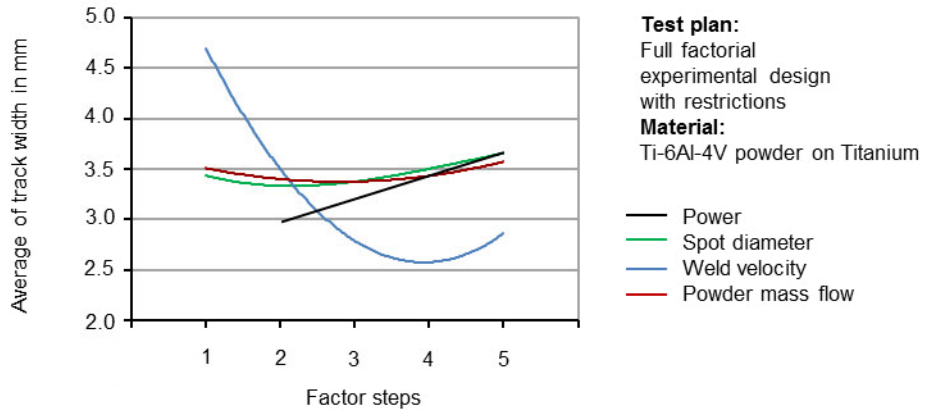

Figure 2. Full factorial test plan: main effects on track width

Table 4. Full factorial test plan: ANOVA for track width

Effect	p-value	Effect	p-value	Effect	p-value
P	0.004	P^2	0.131	P·d	0.010
d	0.969	d^2	0.656	P·v	0.127
v	0	v^2	0	P·m	0.961
m	0.003	m^2	0.08	d·v	0.150
				d·m	0.127
				v·m	0

Laser power and weld velocity have significant effect on the track width. Spot diameter and powder mass flow influence the track width substantially less.

The influence of laser power and travel feed can be explained physically. A higher heat is supplied with a higher laser power to the basic material. Therefore, a bigger and accordingly broader melting pool is formed. Welding beads with a larger width result. With the slightest (evaluable) factor step of 500 W an average width of 3 mm is produced while an average track width of 3.3 mm is applied with 2000 W. Under acceptance of a confidence interval of 95%, the effect strength account between 0.17 mm and 0.37 mm. Therefore, the effect is relatively small.

The track width decreases with increasing weld velocity. Therefore, the effect of the weld velocity is negative. This can be explained by longer retention time, caused by lower speed. Thus, the melt pool geometry is decisively influenced.

Based on the regression function, there is a small influence on the track width, caused by the spot diameter. However, the ANOVA indicates a significant effect. The factor is varied between 0.6 mm and 2.2 mm. Altogether, an effect strength of 0.22 mm can be ascertained. The slight effect can be mostly explained by the introduced power density. A small spot diameter generates high power densities. The heat input is made intently on a small surface. By heat conduction the adjoining area fuses secondarily whereby the width is influenced. With bigger spot diameter the directly molten surface increases accordingly. The previous secondarily heated area is fused directly. This leads to nearly constant track widths despite an enlargement of the spot diameter. The effect is supported by the Gaussian-power distribution of the used laser. A similar result is shown in (Graf et al., 2013) [4].

The ANOVA indicates the power mass flow to be a significant factor, which could not be confirmed by regression. In the process laser metal deposition, powder is supplied to the laser beam shortly before striking on the substrate. The powder is heated up and fuses in the melt pool. Hence, no effect on the melt pool geometry consists. Therefore, the powder mass flow is considered a non-significant factor.

For evaluation of the results model accuracy parameters, standard distance and coefficient of determination are considered. The standard distance S describes data values with regard to the regression function. For the track width, a standard distance of 0.33 mm is determined by the variance analysis. Thus, the medium width scatters 0.33 mm around the average value. For evaluation, it is valid: The better the equation forecasts the values of the answer variable, the lower the standard distance S. Therefore, the value 0 is aimed at. With an amount of 0.33 mm the calculated standard distance is to be assessed sufficiently small. The coefficient of determination R^2 amounts 91.4%. It provides information about the degree of dispersion in observed values of the aim size. As limit a value of 90% is given in literature. Therefore, the coefficient of determination of the track width is above the level. Consequently, the statements about the effects on track width are confident.

3.1.2. *Track height*

The evaluation of the track height is also based on regression functions and the ANOVA.

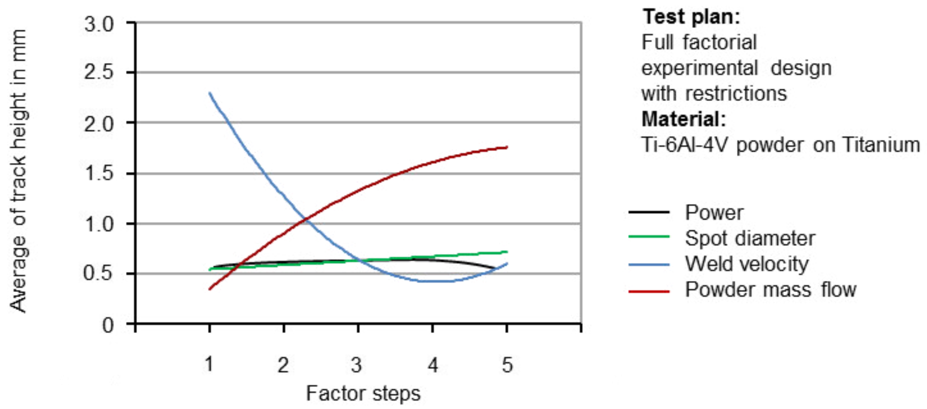

Figure 3. Full factorial test plan: main effects on track height

Table 5. Full factorial test plan: ANOVA for track height

Effect	p-value	Effect	p-value	Effect	p-value
P	0.531	P^2	0.014	P·d	0.008
d	0.762	d^2	0.059	P·v	0.775
v	0	v^2	0	P·m	0.069
m	0	m^2	0.008	d·v	0.002
				d·m	0.221
				v·m	0

Powder mass and weld velocity have a significant effect on the track height, as concluded from the effect diagrams. Laser power and spot diameter seem to have no influence on the track height. The results of the ANOVA lead to the same conclusion.

For construction of high welding beads the quantity of the powder is important. This is regulated by the powder mass flow. During the coating process, powder is piled up on the resulted melted pool. With higher powder mass flow, repeated applying on already available powder particle occurs. Thus, the height increases. Besides, higher layers melt by heat transfer of particles. Regression as well as the ANOVA indicate the effect to be square. The square course can be explained physically. Even if more powder is supplied to the process, it cannot stick to the substrate by the heat input of heat transfer only. Once a certain amount is reached the powder cannot be melted completely. Accordingly, there is an optimum.

In addition, the significant (negative) effect of the weld velocity is understandable. With lower speeds and a constant powder mass flow a higher quantity of powder particles is applied on a surface element. Thus, more powder is made available for layering. Out of this, a higher track height results. Accordingly, the track height decreases with increasing speeds. This effect is favored by the energy per unit length. Thus, a comparatively higher energy per unit length has positive effects with slower feed.

The standard distance S amounts to 0.33. Therefore, it is equivalent to the standard distance of the track width and estimated as small enough. The coefficient of determination R^2 amounts to 90.25%, which is higher than the limit of 90%. That is why the given statements about the effects are assumed as reliable.

3.2. *D-optimum experimental designs*

In the analysis of the D-optimum test plans, focus lies on recognized effects. The meanings of the effects are not repeated. Rather the detected effects are compared to those of the full factorial test plan. Besides model accuracy parameters, standard distance S and coefficient of determination R^2, conditions for the evaluation of design of experiments, normal distribution, homoscedasticity and autocorrelation, are considered.

3.2.1. *Track width*

In the following regression functions of respective factors are illustrated for carried out test plans. Figure 4 represents the regressions functions. Table 6 shows the results of the ANOVA. Furthermore, conditions for evaluation of design of experiments were examined: normal distribution, homoscedasticity and autocorrelation (see Table 7). The results of the full factorial test plan are given as reference values.

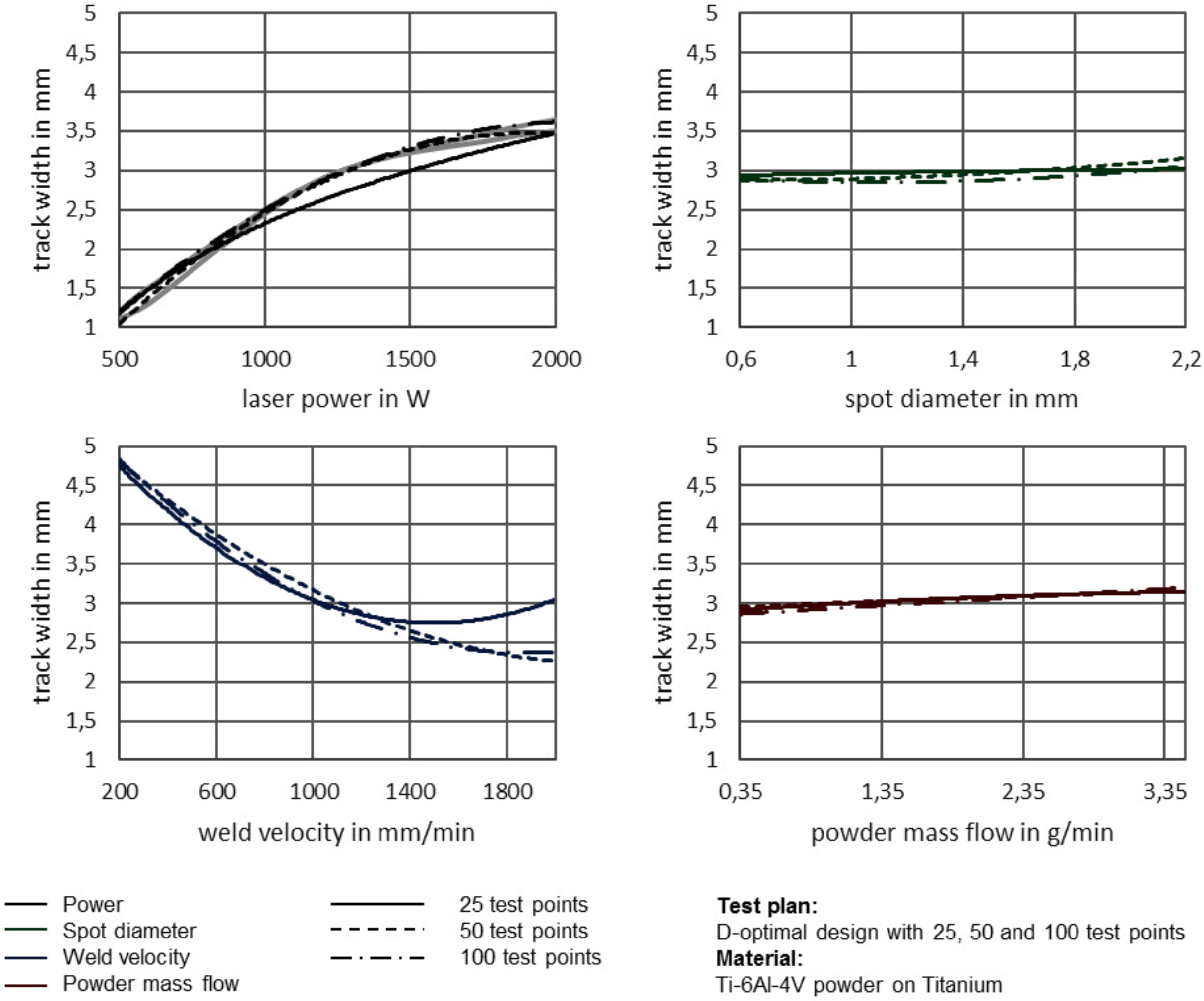

Figure 4. D-optimal experimental designs: main effects on track width

The D-optimum experimental design with 25 test points does not fulfill the criteria for normal distribution, homoscedasticity and autocorrelation. Therefore, the results of the D-Optimum test plan must be assumed non-valid. The D-optimum test plans with 50 and 100 test points fulfill all criteria.

Looking at model accuracy parameters the D-optimum test plan with 25 test points appears to have higher standard distance S. The coefficient of determination R^2 shows no conspicuities. Since the applicability of the D-optimum test plans is investigated, the corrected degree of certainty and the forecasted degree of certainty are considered, too. The value of the forecasted degree of certainty amounts less at 90%. Hence, it can be concluded that an over fit of the model is given. The stability of the model must be questioned. The D-optimum experimental designs with 50 and 100 test points show no strong divergence. To sum up, the D-optimum test plan with 25 test points is classified as not confidential. The D-optimum test plans with 50 and 100 test points fulfill the criteria and are evaluable.

Table 6. D-optimal experimental designs: ANOVA for track width

Effect	p-value			Effect	p-value		
	25 test points	50 test points	100 test points		25 test points	50 test points	100 test points
P	0.18	0	0	P·d	0.508	0.505	0.300
d	0.535	0.150	0.008	P·v	0.084	0.021	0
v	0.026	0	0	P·m	0.121	0.002	0
m	0.457	0.067	0.003	d·v	0.068	0	0
P^2	0.273	0.014	0.001	d·m	0.163	0.084	0.014
d^2	0.659	0.445	0.066	v·m	0.265	0.149	0.002
v^2	0.03	0.001	0				
m^2	0.973	0.701	0.937				

Table 7. D-optimal experimental designs: Criteria for the evaluation for track height

	25 test points	50 test points	100 test points
normal distribution		✓	✓
homoscedasticity		✓	✓
autocorrelation		✓	✓

Table 8 gives an overview of the significant main effects of the different D-optimum test plans in the direct comparison to the full factorial test plan with regard to the target sizes.

Table 8. Comparison of the test plans according to the recognized effects for track width

			P		d		v		m	
			linear	square	linear	square	linear	square	linear	square
D-optimal experimental designs	25 test points	regression	✔	✔			✔	✔		
		ANOVA					✔	✔		
	50 test points	regression	✔	✔			✔	✔		
		ANOVA	✔				✔	✔		
	100 test points	regression	✔				✔	✔		
		ANOVA	✔	✔	✔		✔	✔	✔	
full factorial test plan		regression	✔				✔	✔		
		ANOVA	✔		✔	✔	✔	✔	✔	✔

It could be shown that all carried out D-optimum test plans identify the essential main effects, laser power and weld velocity. The figures indicate the factor laser power to be very squared in contrast to all D-optimum test plans with fewer test points. An optimum of this factor cannot be physically explained. The interpolation is estimated as too strong. The D-optimum test plan with 50 and 100 test points shows a linear influence and is comparable with the reference value. The factors spot diameter and powder mass flow only slightly affect the track width. Thus, it is understandable that these effects cannot be clearly identified with lower quantities of test points. Therefore, the choice of the test points is of vital importance.

3.2.2. *Track height*

The regression functions of the carried-out test plan are subdivided in the investigated factor and are shown in the following. The results of the ANOVA are shown in Table 9. The criteria for evaluation – normal distribution, homoscedasticity and autocorrelation – were also checked. The full factorial test plan serves as reference value.

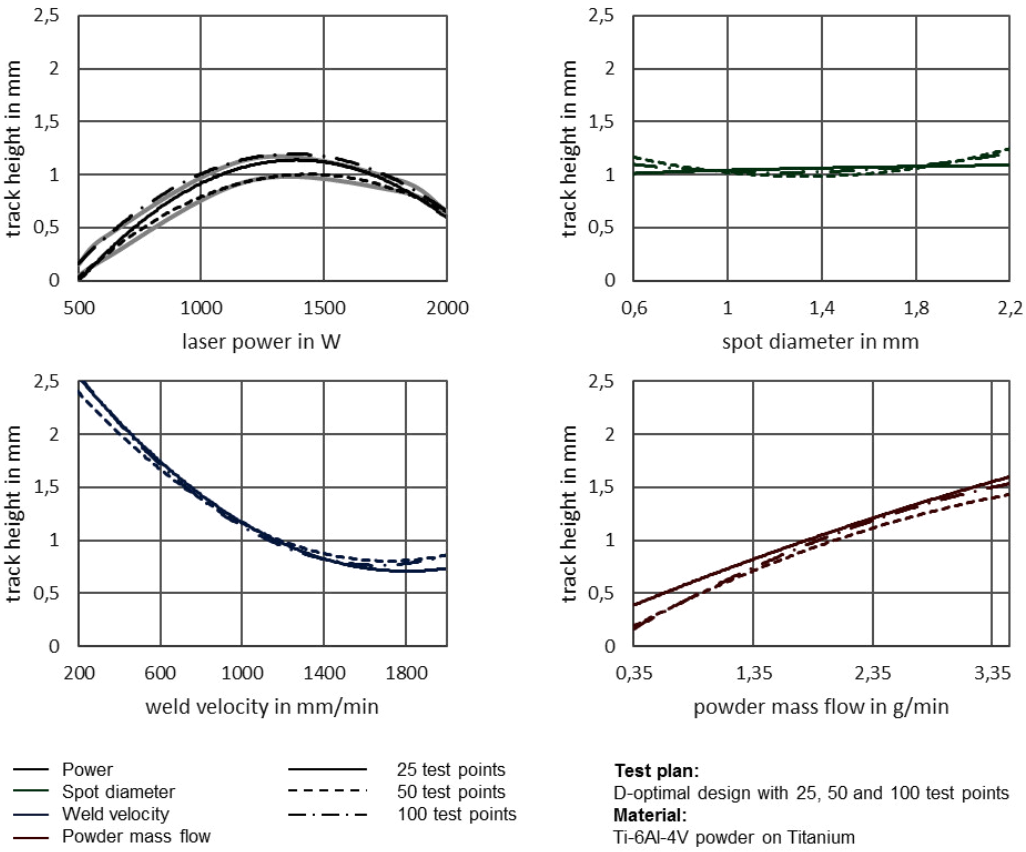

Figure 5. D-optimal experimental designs: main effects on track height

Table 9. D-optimal experimental designs: ANOVA for track height

Effect	p-value			Effect	p-value		
	25 test points	50 test points	100 test points		25 test points	50 test points	100 test points
P	0.312	0.07	0.09	P·d	0.323	0.049	0
d	0.769	0.539	0.240	P·v	0.638	0.371	0.028
v	0.010	0	0	P·m	0.100	0.008	0.026
m	0	0	0	d·v	0.505	0.046	0.002
P^2	0.076	0	0	d·m	0.194	0.168	0.001
d^2	0.917	0.281	0.128	v·m	0	0	0
v^2	0.078	0	0				
m^2	0.986	0.370	0.002				

Table 10. D-optimal experimental designs: Criteria for the evaluation for track height

	25 test points	50 test points	100 test points
normal distribution	✓	✓	✓
homoscedasticity	✓	✓	✓
autocorrelation	✓	✓	✓

The conditions for the evaluations of design of experiments are fulfilled for all carried out D-optimum test plans.

The model accuracy parameters are equivalent to the track width and the standard distance S which is too large for the D-optimum test plan with 25 test points. Therefore, the interpolation is rated as too strong. This can be concluded with help of the forecasted coefficient of determination. With an amount of 71% it is clearly smaller than the limit of 90%. Accordingly, the results of this test plan are to be questioned. The D-optimum test plans with 50 and 100 test points can be classified as reliable because the model accuracy parameters standard distance S is comparable with the one of the full factorial test plan. Furthermore, the coefficient of determination lies above the 90% limit.

Table 11 shows a tabular overview of the investigated factors with regard to their significance. These are compared with the results of the full factorial test plan.

Table 11. Comparison of the test plans according to the recognized effects for track height

			P		d		v		m	
			linear	square	linear	square	linear	square	linear	square
D-optimal experimental designs	25 test points	regression					✔	✔		
		ANOVA					✔			
	50 test points	regression		✔			✔	✔	✔	✔
		ANOVA		✔			✔	✔	✔	✔
	100 test points	regression		✔			✔	✔	✔	✔
		ANOVA		✔			✔	✔	✔	✔
full factorial test plan		regression	✔	✔			✔	✔	✔	✔
		ANOVA	✔				✔	✔	✔	✔

As significant effects for the track height the factors powder mass flow and weld velocity were identified in chapter 3.1.2. Both factors are directly connected with the layering of powder. The laser power has a small influence.

The effect of the weld velocity is recognized with all D-optimum test plans. The strongest effect on the track height is caused by the powder mass flow. This can be shown with all D-optimal experimental designs. In all carried-out D-optimum test plans the factor spot diameter was not assessed as significant.

4. Conclusion

During the check of the model accuracy parameters and the criteria to the condition of a valid evaluation the D-optimum test plan with 25 test points turns out to be invalid. From a statistical point of view, all statements of this test plan are not meaningful. They cannot be considered as scientifically justified results. Not all significant effects are recognized. The quantity of the test points does not seem sufficient to make a valid statement with regard to the effects.

The D-optimum test plan with 50 test points fulfilled the criteria for evaluation. The model accuracy parameters are also good enough. The significance of the effects could be determined for all factors. Hence, this test plan can be recommended for further investigations.

The D-optimum design experimental with 100 test points fulfils the criteria for the evaluation of static test plans. The values of the model accuracy parameters are good. With the application of this test plan all significant main effects of the full factorial test plan can be determined. The execution has needed twice the time to reach the same results that can be drawn from the D-optimal test plan with 50 test points. For this reason, this test plan is only partly recommendable. Table 12 shows an overview of the test plans with regard to time exposure and profit of information.

Table 12. Overview of the test plans with regard to time exposure and profit of information

Experimental design	Amount of test points	time exposure	result precision
full factorial test plan with restrictions	310	21.5 hours	very good
D-optimal experimental design with 25 test points	25	1.65 hours	poor
D-optimal experimental design with 50 test points	50	3.3 hours	very good
D-optimal experimental design with 100 test points	100	6.6 hours	very good

The realization of the full factorial test plan under the use of restrictions lasts for 21.5 hours. This test plan is valid in the present work as reference value. The accuracy of the result of the D-optimum test plans with 25 test points is not ranked high enough. However, the D-optimum test plan with 50 test points indicates a very good result accuracy, especially regarding the main effects. This test plan saves 18 hours and 10 minutes compared to the full factorial test plan, which accounts for approximately 84.5 %.

In summary, the quantity of the test points for D-optimum design experimental has a high meaning. According to the literature, 21 test points are necessary in the researched case. It could be shown that 25 are not sufficient to identify all significant effects. That is why it is recommended to choose the count of the test points in relation to the full factorial test plan. In this case, the D-optimum test plan with 50 test points provides the best results with regard to time exposure and profit of information.

5. Summary and Outlook

This paper deals with the application of design of experiments using restrictions for laser metal deposition. The aim was to evaluate the applicability of D-optimum test plans under use of restrictions by a bigger test space and thus, to increase process knowledge. Titanium alloy Ti6Al4Vwas used as filler material and substrate. The target size was the geometry of the weld beading, which was assessed by track width and track height. As factors laser power, spot diameter, weld velocity and powder mass flow were selected. The factors were varied on five factor steps. To guarantee a regular coating, a subset of the test space was build. Therefore, restrictions were set for energy per unit length, surface energy as well as the molten mass required for cladding.

A full factorial test plan as well as three D-optimum test plans (25, 50 and 100 test points) were carried out under the use of restrictions. The analysis of the full factorial plan provided a basis for comparison with the D-optimum test plans.

Laser power and weld velocity influenced the track width the strongest. Both parameters directly affected the melt pool geometry which was responsible for broadening the track. The spot diameter also caused a small influence on the track width. For the track height, above all the factors the weld velocity and powder mass flow were significant.

In comparison the D-optimum test plan with 25 test points showed the biggest divergences. The examination of the evaluation conditions show the results of this test plan cannot be classified reliable. The D-optimum test plans with 50 and 100 test points achieved good results. Besides, it saves over 80 % of time compared to the full factorial test plan. Above all the application of D-optimum test plans can be recommended for big test spaces (more than three factors). In this context, the flexible design of these test plans offers an essential advantage, for example the uncomplicated use of restrictions. Here, the choice of the quantity of test points has to be calculated in a suitable relation to the full factorial test plan. To enhance the comprehensibility of the process, it is recommended to consider additional target sizes for future researches. With laser metal deposition, for example, metal structures can be additionally generated. Thus, investigations of complicated geometrical forms are useful. In this case, the application of restrictions in D-optimum test plans are meaningful. An adaptation of the restrictions or the development of new restrictions could be valuable as well.

REFERENCES

[1] Arellano-Garcia, H., Schöneberger, J., & Körkel, S. (2007). Optimale Versuchsplanung in der Chemischen Verfahrenstechnik. Chemie-Ingenieur-Technik, 79(10), 1625–1638. https://doi.org/10.1002/cite.200700110 (in German)

[2] Capello, E., Colombo, D., & Previtali, B. (2005). Repairing of sintered tools using laser cladding by wire. Journal of Materials Processing Technology, 164–165, 990–1000. https://doi.org/10.1016/j.jmatprotec.2005.02.075 (in English)

[3] DVS - Deutscher Verband für Schweißen und verwandte Verfahren e.V. (2011). Laserstrahl-Auftragschweißen Merkblatt DVS 3215, (02 11). (in German)

[4] Graf, B., Ammer, S., Gumenyuk, A., & Rethmeier, M. (2013). Design of Experiments for Laser Metal Deposition in Maintenance, Repair and Overhaul Applications. Procedia CIRP, 11, 245–248. https://doi.org/10.1016/j.procir.2013.07.031(in English)

[5] Leunda, J., Soriano, C., Sanz, C., & Navas, V. G. (2011). Laser Cladding of Vanadium-Carbide Tool Steels for Die Repair. Physics Procedia, 12, 345–352. https://doi.org/10.1016/j.phpro.2011.03.044 (in English)

[6] Narva, V. K., Marants, a. V., & Sentyurina, Z. a. (2014). Investigation into laser cladding of steel-titanium carbide powder mixtures on a steel substrate. Russian Journal of Non-Ferrous Metals, 55(3), 282–288. https://doi.org/10.3103/S1067821214030109 (in English)

[7] Paul, C. P., Ganesh, P., Mishra, S. K., Bhargava, P., Negi, J., & Nath, A. K. (2007). Investigating laser rapid manufacturing for Inconel-625 components. Optics and Laser Technology, 39(4), 800–805. https://doi.org/10.1016/j.optlastec.2006.01.008 (in English)

[8] Subramaniam, B. Y. S., Subramaniam, B. Y. S., Lyons, J. W., Lyons, J. W., White, D. R., White, D. R., … Jones, J. E. (1999). Experimental Approach to Selection of Pulsing Parameters in Pulsed GMAW. Welding Journal, (May), 166–172. (in English)

[9] Sun, Y., & Hao, M. (2012). Statistical analysis and optimization of process parameters in Ti6Al4V laser cladding using Nd:YAG laser. Optics and Lasers in Engineering, 50(7),

985–995. https://doi.org/10.1016/j.optlaseng.2012.01.018 (in English)

Application of D-optimum Experimental Designs in Consideration of Restrictions for Laser Metal Deposition

Angelina Marko*[1], Benjamin Graf*[2], Sergej Gook*[3], Michael Rethmeier,***[4]**

[*] Fraunhofer Institute for Production Systems and Design Technology, Pascalstraße 8-9, 10587 Berlin, Germany

[1] ORCID: 0000-0002-6456-4070
WoS ResearcherID: O-8906-2017
e-mail: angelina.marko@ipk.fraunhofer.de ;
[2] ORCID: 0000-0002-7345-9352
WoS ResearcherID: O-7530-2017;
[3] ORCID: 0000-0002-4350-3850
WoS ResearcherID: F-8636-2017
e-mail: sergej.gook@ipk.fraunhofer.de

[**] Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany
[4] ORCID: 0000-0001-8123-6696
WoS ResearcherID: B-9847-2009

Abstract – The process of laser metal deposition can be applied in many ways. Mostly, it is relevant to coating, for repair welding and for additive manufacturing. To increase the effectiveness and the productiveness, a good process understanding is necessary. Statistical test planning is effectual and often used for this purpose. For financial and temporal reasons, a restriction of the test space is reasonable. In this case, it is recommended to use a D-optimal experimental design which is practically applied to extend existing test plans or if process limits are known. This paper investigates the applicability of a D-optimum experimental design for the laser metal deposition. The results are compared to the current results of a full factorial test plan. Known restrictions are used for the limitation of the test space. Ti6Al4 is utilized as substrate material and powder. Comparable results of the D-optimal experimental design and of the full factorial test plan can be demonstrated. However, 80 % of time can be saved by the experimental procedure. For this reason, the application of D-optimal experimental design for laser metal deposition is recommend.

Keywords: Design of experiments, laser cladding, laser metal deposition, cladding parameter, additive manufacturing, repair welding.