Study of variability phenomena during direct metal deposition of nickel based superalloy on residual porosity and microhardness

Alexander Khaimovich, *Maxim* Oleynik*, *Andrey* Balyakin, *Evgeny* Zlobin,
Maria Kudriashova, and *Ekaterina* Nosova

Samara University, 34, Moskovskoe sh., Samara, 443086, Russia

Abstract. The article reveals the influence of the technological regimes of direct laser cultivation, as well as the adverse conditions on the microhardness and the residual porosity of the samples. The speed of movement of the working tool (from 20 mm/s to 30 mm/s, step 5 mm/s), distance between nozzle and surface (9 mm to 13 mm, 2 mm pitch), mass flow (20.5 g/min to 30.7 g/min, 5.1 g/min pitch) and processing pause (32.0 to 48.0, 8.0) were chosen by variable factors. The influence of the mentioned factors on microhardness and residual porosity was determined, a regression model was worked out. The analysis shows that increasing powder flow and process pause reduces the variability of microhardness by the sample' cross-section and increases its mean value, and the effective focusing distance and the melting speed have an uneven effect. The increase in the focusing distance and the melting speed clearly increase the variability of the residual porosity over the cross-section of the sample. The increase in the values of the technological pause and the powder flow have an opposite effect in the influence.

1 Introduction

Nowadays, additive manufacturing is increasingly being introduced into the field of mechanical engineering because it has a number of advantages over traditional production methods such as casting or post treatment of products. These include:

1. Material efficiency: Additive manufacturing uses the required amount of material to avoid overconsumption and reduce costs.
2. Speed and flexibility of production: additive manufacturing technology allows to create products of complex shape and parts without the need for special devices and tools, which allows to quickly change the design of products and.
3. Minimization of waste: In additive production, material waste is minimal, which reduces the negative impact on the environment and increases the sustainability of the production process.

---

* Corresponding author: oleynik1997@mail.ru

4. Ability to create fine and complex structures: additive manufacturing allows for high precision and complex geometric shapes to be created, which may be difficult or impossible to do with traditional methods [1-2].

Despite these advantages, features of the additive technologies used in the production of metal products are not fully understood. The main kinds of the additive technologies used in the direct production of metal parts are direct metal deposition (DMD) and selective laser sintering (SLS). If SLS technology has been used for a relatively long time and an increasing number of manufacturers are supplying their plants for production (which means that the technology is well-used), DMD technology is rarely used in engineering, due to the low understanding and complexity of the process and the low number of DMD plant manufacturers on the market [1,3,4].

In addition to the disadvantages of the DMD technology described above, the direct metal deposition process has low stability and often requires rapid intervention when growing the workpieces to avoid the occurrence of a match. Thus, the miss-defined mass consumption of the powder leads to two cases:

- High flow produces a large and unstable melting bath, which leads to distortion of the geometry and curvature of the layer being overflowed, which in the process of cultivation leads to the multiplying of distorted layers and the appearance of marriage;
- At low melt flow rate, the powder quantity is insufficient, resulting in a difference between the actual height and the calculated swaging roller. This causes the distance between the nozzle and the formed layer to increase, which causes the gas powder jets to focus [5-7].

The task of optimizing the technological modes of bonding is multi-criteria both in the number of independent variables and in the number of dependent variables - the characteristics of the quality of bonding. Among the characteristics that allow to evaluate the quality of the products obtained is the porosity. It can be as a consequence of the implementation of certain DMD regimes, and also depend on the quality, and more precisely, the porosity of the original metal powder composition. Among the mechanical properties that allow to evaluate the influence of DMD parameters on the quality and structural changes in the material of the product, one can highlight microhardness. Both of these characteristics can be evaluated in the local cross-sectional areas of the product with high precision.

Some methods of multi-criteria optimization of the modes of fusion are given in the study [8]. It should be borne in mind that due to the instability of the alloy process, the optimal alloy parameters for minimizing the variability of the quality of the products may differ from the recommended ones. The influence of variability of technological parameters is studied in this article. In particular, the effect of focusing gas dust jets by changing the distance between the nozzle and the formed layer is investigated, as well as the effect of the mass flow of the powder on the microhardness and the residual porosity. In addition, the microhardness and residual porosity of cultivation process modes, such as the speed of the nozzle movement and the technological pause, which is used to ensure that between the successive laser inclusions. The product you're growing has not been overheated.

2 Experimental section

The study was conducted at the direct metal deposition plant ILIST-L (Russia, Saint Petersburg) with a four-jet coaxial nozzle. The grown samples are parallelepipeds with sides of 30×10×10 mm. Figure 1 shows the DMD process. The material of the samples is a chromium–nickel heat-resistant alloy HN50VMTUB, the chemical composition of which is presented in Table 1.

Table 1. Chemical composition HN50VMTUB.

Ni	C	S	P	Mn	Cr	W	Ti	Si	Nb	Mo	Fe	Ce	B	Al
base	≤0.10	≤0.010	≤0.015	≤0.50	32.0-35.0	4.30-5.30	0.50-1.10	≤0.40	0.50-1.10	2.30-3.30	≤4.00	≤0.030	≤0.008	0.50-1.10

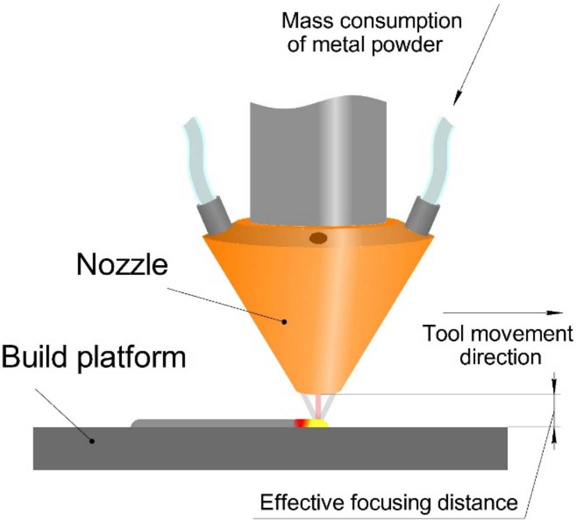

Fig. 1. The DMD process.

Microhardness and porosity measurements were carried out on the central cross sections of the samples. It should be noted that in the process of growing samples with a planned rectangular cross-section, the geometry changes and the formation of beveled corners occurs, as shown in Figure 2. Microhardness was measured at 9 cross-section points, the location of which is shown in Figure 2.

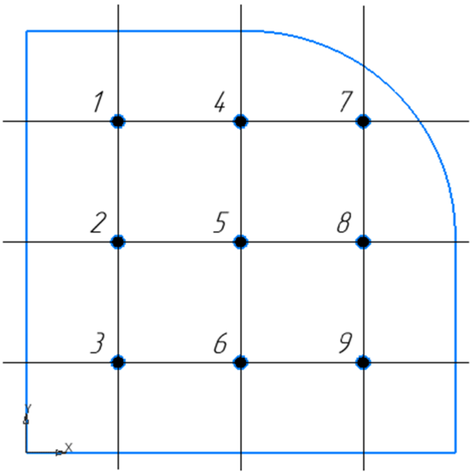

Fig. 2. Location of control points in the sample section.

The variability of the DMD process and the quantitative assessment of the influence of factors (technological parameters) on residual porosity and microhardness were studied experimentally using the robust Taguchi L9 plan. The plan of the experiment in kind is shown in Table 2.

Table 2. The plan of the experiment.

Mode	Speed V, mm/s	Effective focusing distance F, mm	Powder cons. q, g/min	Pause t, s
1	20	9	20.5	32
2	20	11	25.6	40
3	20	13	30.7	48
4	25	9	25.6	48
5	25	11	30.7	32
6	25	13	20.5	40
7	30	9	30.7	40
8	30	11	20.5	48
9	30	13	25.6	32

The response parameters are shown in Table 3. HVavg is the average microhardness at 9 points, Sigma_HV is the standard deviation of microhardness, Cv=Sigma_HV/HVavg is the coefficient of variability. SS of AVpor is the sum of the squares of the porosity deviations from the average value, SS of AVpor/(1- AVpor) is the sum of the squares of the relative porosity deviations from the average value, where AVpor/(1– AVpor) is the relative porosity.

Table 3. Parameters of experimental responses.

Mode	HVavg	Sigma_HV	Sigma_HV/ HVavg	Average porosity (AVpor), 10^{-2}	SS of AVpor, 10^{-3}	SS of AVpor/(1- AVpor), 10^{-3}
1	366	72	0.198	1.778	0.355	0.362
2	363	45	0.123	2.556	0.622	0.638
3	369	29	0.0079	2.556	1.022	1.049
4	303	21	0.070	1.778	0.155	0.158
5	371	33	0.089	2.778	0.955	0.982
6	336	43	0.128	1.222	0.155	0.157
7	362	35	0.098	2.222	0.355	0.363
8	348	40	0.115	2.444	0.622	0.637
9	382	69	0.180	4.889	3.289	3.458

2.1 Correlation analysis

At the first stage, a correlation analysis was carried out for all factors – independent (technological parameters) and dependent – quality indicators (responses) for residual porosity and microhardness. The results of the correlation analysis are presented in Table 4.

Correlation analysis shows that variation of technological factors within their ranges of variation does not have a statistically significant effect on responses (dependent parameters – quality indicators), except for the effect of a technological pause on the coefficient of variation of fused samples Cv=Sigma/HVavg.

Basically, this conclusion concerns the spread of microhardness values, so the correlation coefficient between the coefficient of variation of microhardness Cv and the technological pause is r = -0.669, and between the average value of NV according to the sample and the technological pause is r = -0.609.

Table 4. Spearman correlation matrix.

	Speed V	**Effective focusing distance F**	**Powder cons. q**	**Pause t**	**Cv= Sigma/HVavg**	**SS of AVpor/(1-AVpor)**
Speed V	1.000000	-0.0	0.0	0.0	-0.0240	0.340
Effective focusing distance F	0.0	1.000000	-0.0	0.0	0.069	0.533
Powder cons. q	0.0	0.0	1.0	0.0	-0.576	0.175
Pause t	0.0	0.0	0.0	1.0	-0.669	-0.417
Sigma_HV/ HVavg	-0.024	0.069	-0.576	-0.669	1.0	0.408
SS of AVpor/(1-AVpor)	0.340	0.533	0.175	-0.418	0.408	1.0

Powder consumption has a slightly lower effect on microhardness with a correlation coefficient of r = -0.576. The greatest effect on residual porosity (AVpor/(1- AVpor)) it has an effective focusing distance with r = 0.533. The influence of other technological factors is an order of magnitude less. Microhardness parameters and residual porosity parameters are poorly correlated with each other. The highest correlation coefficient r = 0.535 is observed between the standard deviations of porosity and microhardness.

2.2 Regression analysis

The purpose of regression analysis is to obtain regression dependencies (in our case, of the second order from the effects of the main factors without taking into account paired interactions) to assess the influence of technological parameters (independent variables) on the dependent parameters (responses) of microhardness and residual porosity.

The significance of the regression coefficients was determined by t-statistics with a significant confidence level of $p<0.05$. The regression equation for the coefficient of variation of microhardness Cv has the form:

$$Cv = 1.259 - 0.0731V + 0.00146V2 - 0.000113q2 - 0.004252t,$$

here V is the laser speed, mm/s, q is the powder consumption, g/min, t is the technological pause, s.

The regression equation for the relative porosity of AVpor has the form:

$$AVpor/(1- AVpor) = -0.009922 + 0.001767F - 0.000077F^2 + 0.000001q^2,$$

Here F is the effective focusing distance, mm, q is the powder consumption, g/min.

The adequacy of regression models was assessed by the multiple determination coefficient R-squared (R2) for microhardness parameters (Table. 5) and the parameters of residual porosity (Table 6). The R-square is a statistical measure of agreement with which it is possible to determine how well the regression model corresponds to the data on which it is built.

$$R^2 = 1 - \frac{\partial^2}{\partial_y^2} = 1 - \frac{\frac{SS_{res}}{n}}{\frac{SS_{tot}}{n}} = 1 - \frac{SS_{res}}{SS_{tot}},$$

where

$$SS_{res} = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

is sum of the squares of the regression residuals;

$$SS_{tot} = \sum_{i=1}^{n} (y_i - \bar{y}_i)^2 = n\hat{\sigma}_y^2$$

is total sum of squares.

For a more adequate assessment, an adjusted value R2 is used, taking into account the limitations of the degrees of freedom k, equal to the number of regression coefficients

$$\mathrm{R}^2_{adj} = 1 - \frac{s^2}{\partial s_y^2} = 1 - \frac{\frac{SS_{res}}{n-k}}{\frac{SS_{tot}}{n-1}}.$$

Table 5. Multiplication coefficients R-squared determinations for microhardness parameters.

Dependent variable	Plenty R	Plenty R2	Plenty R2
Cv=Sigma/HVavg	0.977	0.955	0.909

Table 6. Multiplication coefficients. R-squared determinations for residual porosity parameters.

Dependent variable	Plenty R	Plenty R2	Plenty R2
AVpor/(1- AVpor)	0.843	0.711	0.495

As can be seen from the data from Tables 5 and 6, the model of microhardness parameters has a higher adequacy in comparison with regression for residual porosity parameters. This can also be seen from the graphs of the observed and predicted values of the microhardness and residual porosity parameters, Figure 3 and Figure 4, respectively.

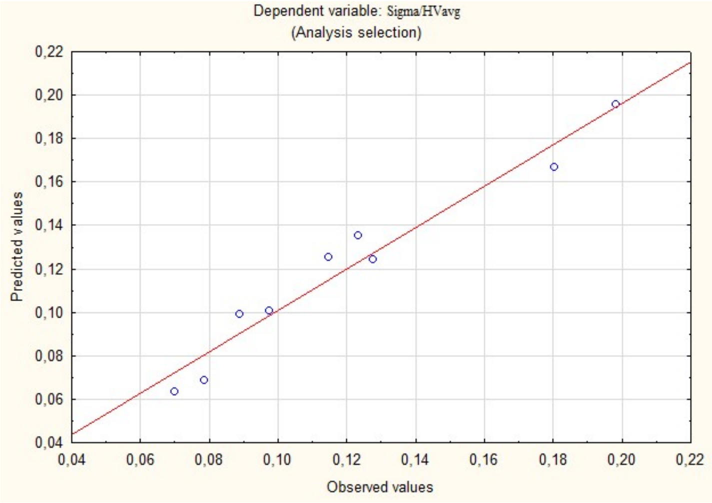

Fig. 3. Observed and predicted values of microhardness parameters.

The analysis of the influence of variability of factors (independent variables – technological modes) on the microhardness of fused samples was determined based on the Taguchi principle "less is better". Graphs of the average values of the ETA – useful signal-to-noise ratio are shown in Figure 5. Optimal from the point of view of minimizing geometry distortions are the parameters of the technological modes of fusion presented in Table 7.

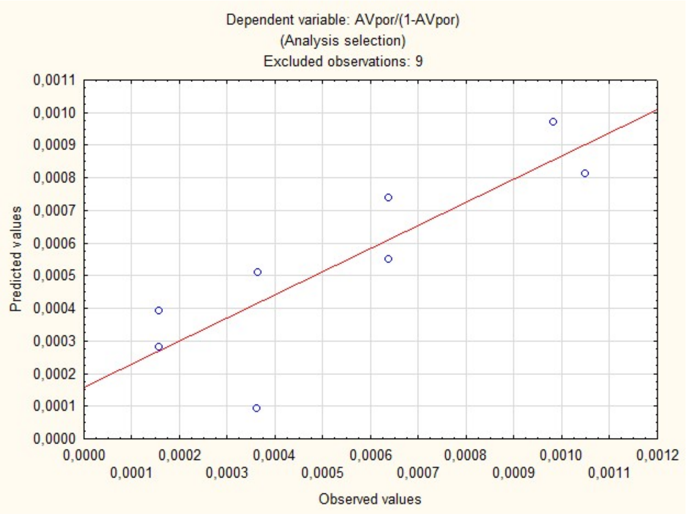

Fig. 4. Observed and predicted values of residual porosity parameters.

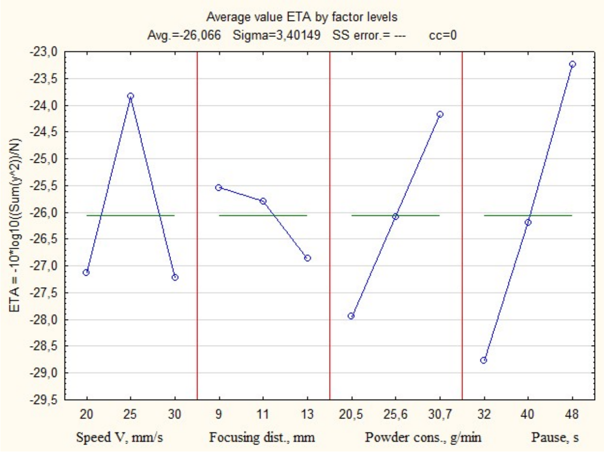

Fig. 5. The average signal-to-noise ratio of responses according to microhardness parameters by factor levels.

Table. 7. Expected signal-to-noise ratio under optimal conditions.

Factor	**Expected S/N ratio under optimal conditions Average -26.066 Sigma 3.40149**	
	Level	**Effective size**
Speed V, mm/s	25	2.22
Effective focusing distance F, mm	9	0.526
Powder cons. q, g/min	30.7	1.89
Pause t, s	48	2.82
Expected signal/noise		-18.59

2.3 Factor analysis

Factor analysis establishes relationships between variables, identifies the main factors that influence responses. This method allows you to reduce the number of variables and define them into structured groups of more generalized factors, which simplifies data analysis.

Table 8 shows the result of factor analysis for two groups of factors. An analysis of the calculation of factor loads obtained by the main axis method shows that the statistically significant response factors from the first group (factor group 1) include only the parameter of residual porosity AVpor, Deviation of AVpor, Deviation of AVpor/(1- AVpor) with factor loads greater than 0.74. The group of the second factor, taking into account statistical significance, includes only the microhardness parameter Sigma_HV/HVavg, with a factor load of 0.72. It should be noted that the responses of groups of variables combined into factors are counterdirectional, i.e. with a decrease in residual porosity (component of factor 1), the values of the variable microhardness level (component of factor 2) increases. For further research, it is advisable to consider one significant factor (response variable) from each group, since all significant factors in each group of factors 1 and 2 have factor loads of comparable magnitude.

Table 8. Calculation of factor loads.

Variable	Factor 1	Factor 2
HVavg	-0.763	0.033
Sigma_HV	-0.749	0.658
Sigma_HV/HVavg	-0.679	0.720
AVpor	-0.888	-0.431
Deviation of AVpor	-0.925	-0.339
Deviation of AVpor/(1- AVpor)	-0.925	-0.336
Total dispersion	4.103	1.367
Share of total	0.684	0.228

3 Conclusion

As a result of the study, it was possible to obtain the dependence and strength of the influence of DMD factors on microhardness and residual porosity. According to the principal component method, the projection of variables onto the factor plane was analyzed (Figure 6).

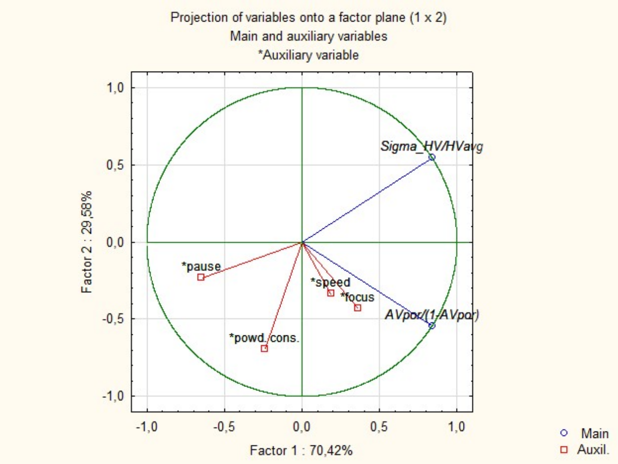

Fig. 6. Projection of variables onto the factor plane.

Responses are presented as the main variables, and variables of technological parameters are presented as auxiliary. A change in the generalizing factor 1 provides a load change of 70% of the total effect of the variables. Analysis of the influence of a group of variables included in generalizing factors 1 and 2 shows that an increase in powder consumption and technological pause unambiguously reduces the variability of microhardness over the sample section and increases its average value, and the effective focusing distance and fusion rate have an ambiguous effect – in the group of variables of the more significant first factor, they contribute to an increase in variability and a decrease in the average value of microhardness, and in the group of variables of the second factor, they have the opposite effect. As for the parameters of residual porosity, an increase in the focusing distance and the fusion rate unambiguously increases the variability of residual porosity over the sample cross-section. An increase in the values of the variables of the technological pause and powder consumption have a counter-directional effect in the context of the influence of both generalizing factors 1 and 2. But, given the dominant influence of variables in the 1st group of factors, an increase in technological contributes to a decrease in the spread of residual porosity.

The study was carried out at the expense of a grant from the Russian Science Foundation № 24-19-00765, https://rscf.ru/project/24-19-00765/.

References

1. R. Mahamood, E. Akinlabi, M. Shukla, S. Pityana, Engineering Letters **21**, 18-22 (2013).
2. N.S. Patel, Priyansh Parihar, Surbhi Makwana, Materials Today: Proceedings **47(11)**, 2709-2714 (2021).
3. M. Erinosho, E. Akinlabi, S. Pityana, Advanced Materials Research **1016**, 177-182 (2014). https://www.doi.org/10.4028/www.scientific.net/AMR.1016.177
4. A. R. Balachandramurthi, J. Moverare, Materials **12(1)**, 68 (2018).
5. E.A. Nosova, A.V. Balyakin, M.A. Oleynik, Physics of the Solid State **65**, 32-35 (2023).
6. D. Dye, O. Hunziker, R.C. Reed, Acta Materialia **49(7)**, 683-697 (2001).
7. R. Sampson, R. Lancaster, Optics & Laser Technology **127**, 106194 (2020).
8. A.V. Agapovichev, A.I. Khaimovich, V.G. Smelov, V.V. Kokareva, E.V. Zemlyakov, K.D. Babkin, A.Y. Kovchik, Materials **16(5)**, 2088 (2023).