IMPACT OF FRACTAL PARAMETERS OF POWDER-BED PACKING ON PART QUALITY AND PROCESS PERFORMANCE IN SLS PRINTING OF MECHANICAL ENGINEERING COMPONENTS

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Abstract. This paper investigates the influence of a combined fractal characteristic of the powder layer on the quality and thermomechanical properties of SLS-manufactured parts. Conventional approaches are limited to analysing surface parameters of the layer and do not account for its spatial structure, which reduces the reliability of defect prediction. The aim of the study is to develop a new approach to the integrated assessment and quality control of SLS printing by analysing the fractal parameters of each powder layer. A digital model of layer packing was developed to enable real-time evaluation of non-uniformity and prediction of defects at the layer-formation stage. In this study, the combination of the fractal dimension and the void clustering index (P_k) serves as a generalised descriptor of densification, structural complexity, and potential thermal conductivity. The proposed method is based on voxel reconstruction of the powder model and its “stratification” into sublayers, combined with box-counting in Mathcad and numerical modelling in MagicaVoxel, CINEMA 4D, and SolidWorks Simulation. The results show that, as clustering increases, the fractal dimension decreases, thermal barriers form, and the temperature of the lower layers drops to critical values (~130 °C), leading to residual deformations. Optimal parameters are achieved for a spherical particle 20-50 µm in size, ensuring a fractal dimension of 2.8-2.9 and a clustering index of $P_k \leq 0.16$. An approach to powder-layer correction via pre-compaction (piezo-vibration simulation) is proposed; it reduced the number of voids by 24%, the cluster volume by 47%, increased the temperature of the lower layer to ≈200 °C, and decreased residual deformations by 17%. It is demonstrated that fractal analysis can serve not only as a diagnostic but also as a corrective tool for developing real-time adaptive control systems for SLS printing, substantially improving the quality and reliability of additive manufacturing.

Keywords: selective laser sintering (SLS), fractal dimension, clustering index, voxel model, SLS computer modelling, powder layer.

Introduction

Additive technologies, in particular selective laser sintering (SLS), enable the fabrication of complex parts for the mechanical engineering sector with high accuracy and minimal material consumption. At the same time, product quality is largely determined by the condition and characteristics of each individual powder layer, in particular its uniformity, density, and morphology.

Conventional monitoring methods are based on statistical particle parameters (size, sphericity, packing density); however, they do not reflect the spatial complexity and heterogeneity of the layer. Fractal dimension serves as a universal indicator of structural chaoticity and self-organisation, thereby opening possibilities for predicting part properties and optimising the printing process.

In this study, a concept is proposed in which the fractal dimension is employed as a controllable parameter in powder-based 3D printing technologies. A methodology for its calculation is developed, and prospects for establishing an automated real-time control system aimed at improving print quality are outlined.

Contemporary research in additive manufacturing increasingly focuses on the spatial characteristics of powder layers in SLS 3D printing. Among the promising metrics, fractal dimension is highlighted as it enables assessment of layer heterogeneity and spatial organisation.

Studies [1; 2] have demonstrated a correlation between the fractal dimension of the powder surface and the strength of the manufactured parts; however, the dynamics of structural changes during layer deposition were not considered. Investigations [3; 4] confirmed the influence of fractal dimension on thermal conductivity and sintering efficiency, yet the relationship with the final part characteristics was not systematised. In [5], a defect-identification algorithm based on fractal heterogeneity was proposed; nevertheless, it proved computationally demanding and insufficiently accurate. In [6], the dynamics of changes in fractal dimension across deposition cycles were examined, but without a quantitative evaluation of their impact on part properties. In [7], a relationship between particle sphericity and fractal

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dimension was established, albeit without practical recommendations. Studies [8; 9] revealed an association between porosity and the fractal characteristics of the layer; however, the effect of the powder's rheological properties during spreading was not taken into account.

The literature review indicates the absence of automated real-time systems for monitoring the fractal dimension, the lack of a systematic understanding of how its parameters affect the final characteristics of parts (accuracy, strength, and economic indicators), as well as the absence of feedback mechanisms for regulating the SLS printing process. Under these conditions, unlike the above studies, which mainly focus on individual surface or structural characteristics of the powder layer, an appropriate approach to assessing the quality of its packing is based on stratifying the model into sublayers and analysing two independent parameters, namely fractal dimension and the void clustering index within each sublayer. Therefore, a relevant task for advancing the technology is to develop a method for real-time print-quality control by correcting the fractal characteristics of the powder layer at the stage of its deposition.

The aim of this study is to develop an innovative method for assessing and controlling the quality of additive manufacturing of objects (in particular, selective laser sintering) by analysing and regulating the fractal parameters of powder-layer packing during the 3D printing process.

To achieve this aim, the following objectives are formulated:

- to develop a method for the combined assessment of the fractal parameters of a volumetric powder layer formed by particles of different morphology;
- to create a simulation-based voxel model of powder-layer formation for SLS;
- to propose a method for controlling 3D printing quality by regulating the combined fractal characteristics of each layer within simulation models.

Materials and methods

The object of the study is the 3D printing process using selective laser sintering (SLS). The subject of the study is the influence of the combined fractal parameters of the powder layer, formed at each printing stage, on printing accuracy, strength, uniformity, and energy efficiency.

The main research hypothesis is that the fractal properties of the layer can serve not only as a descriptor of its microstructure but also as a controllable parameter within a closed-loop printing cycle. During the formation of each layer prior to sintering, the layer structure is assessed, its voxel model is constructed, fractal characteristics are computed, and decisions are made regarding physical intervention on the layer (compaction, vibration). The hypothesis formulation is based on the results reported in [10], in which approaches to analysing fractal structures in a discrete representation were validated and are applied in the present work to address additive manufacturing problems.

The study is grounded in a combination of numerical modelling, computer-based image processing, and fractal analysis. It includes:

- modelling of powder-particle packing and construction of a voxel-based 3D model in the MagicaVoxel environment (Fig. 1);
- "stratification" of the model into sublayers with a height of approximately 20 µm (Fig. 2) and calculation of fractal characteristics using the box-counting method;
- simulation of the thermal and stress state of the layer during laser sintering using SolidWorks Simulation tools;
- modelling of layer correction through compaction (piezo-vibration simulation) and repeated calculation of fractal characteristics, as well as the thermal and stress state of the powder layer for subsequent comparison.

For voxel-based analysis, the generated powder-layer models were discretised into cubic cells and stratified into sublayers approximately 20 µm in height. The fractal dimension of each sublayer was determined using the box-counting method, after which the combined characteristic of the corresponding layer was calculated on the basis of the set of sublayer parameters.

Assumptions adopted: powder particle size of 20-80 µm; each layer is considered uniform with a thickness of 100 µm, yet internally heterogeneous in terms of fractal indicators; particle distribution is random; the effects of temperature, humidity, and electrostatic phenomena were not considered.

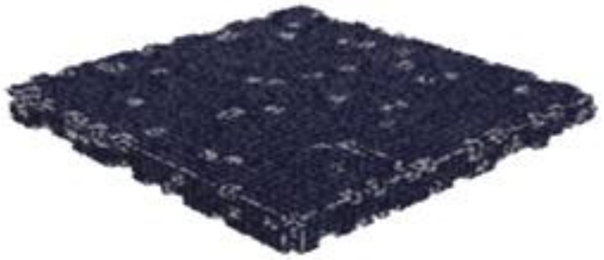

Fig. 1. **Voxel powder-layer model derived from particle-packing animation**

Fig. 2. **Stratification of the 3D powder-layer model into voxel sublayers**

In the thermal simulations, the upper surface was subjected to laser heating, while heat exchange with the surrounding medium and the build platform was taken into account through simplified boundary conditions. Compaction was modelled by reducing the number and volume of void clusters within the voxel structure, thereby simulating the effect of preliminary piezo-vibration treatment of the layer.

Results and discussion

1. Development of a method for assessing the fractal characteristics of a powder layer

Existing methods for determining fractal dimension in SLS technologies are, as a rule, limited to analysing the surface of the powder layer, although print quality is governed by its entire spatial structure. Assessing particle density within the layer thickness makes it possible to detect local defects, estimate the penetration depth of laser radiation, and, consequently, influence the process performance indicators of the printed part.

The results reported in [11] outlined general principles for determining and evaluating the fractal properties of objects in a two-dimensional space by means of planar “stratification” of models. These developments formed the basis for the subsequent elaboration of a three-dimensional strategy for analysing powder layers in SLS technology, which enabled the extension of fractal analysis to additive manufacturing processes.

As a continuation of this line of research, the present work proposes a fundamentally new combined approach to assessing the fractal parameters of powder-layer packing. The approach employs voxel reconstruction of each three-dimensional layer model and its “stratification” into elements (sublayers) of a two-dimensional space. The fractal dimension of the layer is determined as the sum of the dimensions of its individual two-dimensional sublayers:

$$D_n^3 = \sum_1^k DR_k^2\,,\ DR_k^2 = \frac{\ln\left(\sqrt[\alpha]{\eta} \times \beta^{\left(\frac{W_k}{N_k}\right)}\right)}{\ln(\alpha)}\,, \tag{1}$$

where α – discrete scale;

β – stratification parameter defining voxel-model subdivision into sublayers: $\beta^{\alpha} = N_n$;

η – matching function used to establish the relationship between the parameters of individual sublayers and the characteristic of the combined layer: $\eta = \dfrac{W_n}{\beta^{\sum_1^k\left(\frac{W_k}{N_k}\right)}}$;

k – index of the stratification sublayer;

N – number of grid cells in the voxel model;

W – number of occupied voxels.

To provide a quantitative assessment of spatial heterogeneity, an additional parameter is introduced – the void (pore) clustering index, which reflects the number of voids and their connectivity within a given scale. It is defined in a normalised form as:

$$P_k(\alpha) \approx \frac{C_{cavity}(\alpha)}{A(\alpha)}, \tag{2}$$

where $P_k(\alpha)$ – degree of relative void clustering;
$C_{cavity}(\alpha)$ – number of unique voids at the adopted discrete scale;
$A(\alpha)$ – total relative void volume.

Thus, a combined fractal characteristic of the layer is introduced, described by two parameters:

- the fractal dimension D_n^3, which characterises the degree of filling and structural complexity;
- the clustering index $P_k(\alpha)$, which reflects local porosity and heterogeneity.

In the following discussion, D_n^3 is used as the general indicator of layer filling, whereas $P_k(\alpha)$ characterises the degree of local void clustering.

The combination of these indicators (the fractal characteristic) forms a morphological space in which each structure occupies a unique position, making it possible to predict defects and particle densification processes during sintering more accurately.

The analysis of the obtained models showed that, with increasing clustering, the fractal dimension decreases. This indicates a reduction in heat-transfer efficiency, the emergence of local thermal barriers, and a higher probability of defects during sintering.

Therefore, the proposed method enables not only a quantitative assessment of the morphological complexity of a powder layer but also prediction of its influence on the thermal regime and the quality of 3D printing.

2. Development of a simulation model for powder-layer formation in selective laser sintering

To investigate the influence of particle morphology on fractal characteristics, a set of simulations was created in CINEMA 4D with variation of the geometric parameters of the powder – particle size, shape, and the randomness of packing (Fig. 3). The resulting models were voxelised, stratified into sublayers, and imported into SolidWorks for geometric, fractal, and thermal analysis (Fig. 4).

Fractal characteristics were calculated using equations (1) and (2), including the fractal dimension D_n^3 and the void clustering index $P_k(\alpha)$. Mathcad was used to automate the calculations.

Example: for a layer composed of 20–30 μm particles in the form of icosahedra, the following sublayer fractal dimensions were obtained: $D_1^2 = 1.84$, $D_2^2 = 1.81$, $D_3^2 = 1.83$, $D_4^2 = 1.82$, $D_5^2 = 1.84$; the fractal dimension of the 3D voxel model of the layer was $D_n^3 = 2.75$, and the relative void clustering index was $P_k = 0.182$. This indicates high space filling in the absence of pronounced scale self-similarity (a pseudo-fractal structure). The voids had a polyhedral shape, were isolated, and were uniformly distributed throughout the volume.

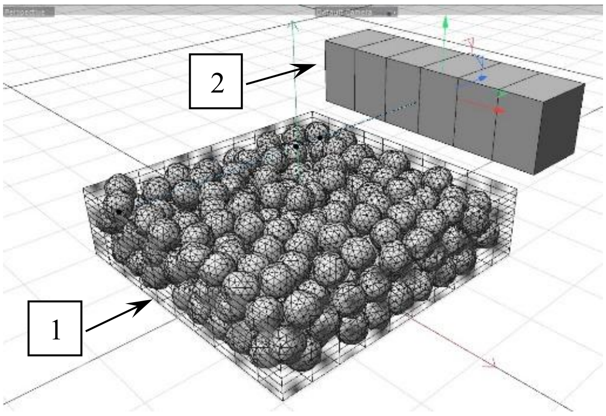

Fig. 3. **CINEMA 4D simulation of powder-layer formation:** 1 – powder layer; 2 – recoater blade

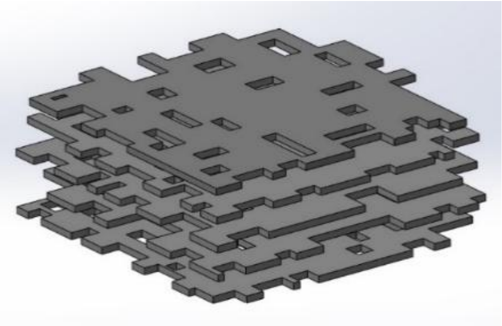

Fig. 4. **Sublayer stratification for fractal and clustering analysis**

The simulation results (Table 1) show that, as clustering increases, the fractal dimension of the layer decreases. Optimal characteristics are achieved for particle sizes of 20-50 μm and a shape close to spherical. This ensures a stable layer thickness (≈100 μm), good flowability, and minimises the risk of pore formation in the finished parts.

The obtained data confirm that particle morphology directly affects the parameters of fractal dimension and clustering and, consequently, the thermal characteristics of the layer. The presence of isolated pores at small scales is not critical; however, under excessive clustering they transform into thermal barriers, which disrupt the uniformity of the temperature field and increase the risk of defects in SLS-printed parts. In Table 1, the assessments of the structural packing density and the nature of pore distribution were assigned according to the simulated combinations of fractal-dimension values and the void clustering index. In this case, higher fractal-dimension values and lower clustering values correspond to denser particle packing and a more uniform pore distribution. Thus, the simulation model makes it possible to determine optimal powder parameters for forming a high-quality layer, which is a prerequisite for further process optimisation.

Table 1

Influence of geometric and fractal characteristics on powder-particle packing structure

Particle size, μm	Particle shape	Fractal dimension of the layer model	Relative void clustering index	Structural packing density	Uniformity of pore distribution
< 20	spherical	> 2.85	0.10-0.13	high	uniform distribution
< 20	hexahedron	> 2.80	0.14-0.15	medium	highly non-uniform
20-30	spherical	> 2.75	0.16-0.18	high	uniform distribution
20-30	icosahedron	> 2.75	0.17-0.19	medium	locally non-uniform
30-50	spherical	> 2.7	0.17-0.19	medium	uniform distribution
30-50	octahedron	> 2.65	0.21-0.22	low	highly non-uniform
> 50	spherical	> 2.6	0.20-0.21	low	locally non-uniform
> 50	octahedron	> 2.55	0.21-0.22	low	clustered porosity

3. Simulation of the thermal and stress state of a powder layer during laser sintering with consideration of particle morphology and compaction

The efficiency of SLS is largely determined by heat losses and by the non-uniformity of the temperature field within the powder layer. To investigate these phenomena, numerical modelling was carried out in SolidWorks Simulation using voxel models of multilayer structures.

The simulation programme included: determination of the temperature gradient from the top to the bottom plate; assessment of the influence of variable sublayer porosity on heat-transfer efficiency; and identification of residual-stress zones.

Polyamide PA12 was assigned the following properties: $\lambda = 0.25\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$, $C_p = 1700\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$, $\rho = 1010\ \mathrm{kg \cdot m^{-3}}$. The laser heated the surface to 250 °C, while the melting temperature was ≈190 °C. A steady-state thermal analysis was performed, accounting for convection and heat exchange with the build platform.

Simulation experiments with a voxel model of a multilayer structure (Fig. 5), characterised by a fractal dimension of $D_n^3 = 2.75$ and a high relative void clustering index of $P_k = 0.18$, revealed a substantial number of randomly distributed voids in the sublayers. This significantly reduced the effective thermal conductivity of the model and, consequently, the temperature of the lower layers. As a result, pronounced non-uniformity of thermal expansion occurred in individual sublayers; an example of their deformations and the bending of the entire model is shown in Fig. 6.

The calculations showed that sublayers with high pore clustering exhibit greater heat losses. In the baseline model, the temperature of the lower layer decreased to ≈130 °C, which is critical for high-quality sintering. In zones with large voids, local thermal barriers were observed (temperature drops of up to 50 °C).

Optimisation of the powder-layer packing geometry (piezo-vibration simulation) reduced the number of voids by 24% and the cluster volume by 47% (Fig. 7), increased the fractal dimension ($D_n^3 = 2.86$), and decreased the void clustering ($P_k = 0.126$). As a result, heat losses decreased by 42%, the temperature of the lower layer increased to ≈200 °C, the difference in thermal expansion decreased by 9%, and residual deformations by 17%. An example of the change in the stress state of the modified model is shown in Fig. 8.

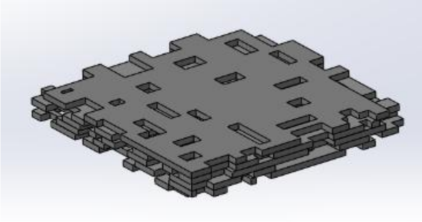

Fig. 5. **Initial voxel model of the powder layer with voids in SolidWorks Simulation**

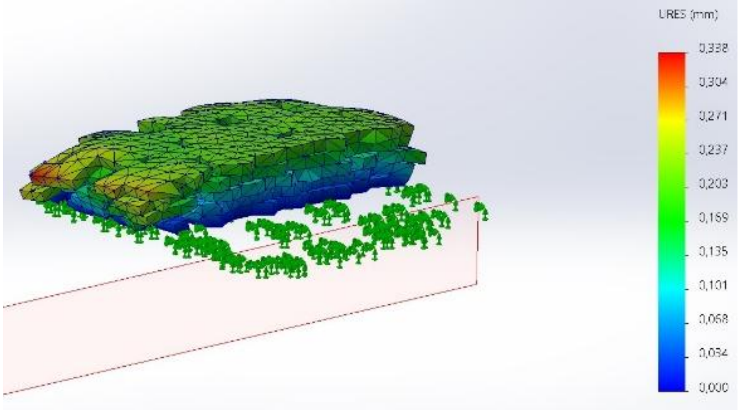

Fig. 6. **Stress-strain state (displacement) analysis of the initial voxel powder-layer model in SolidWorks Simulation**

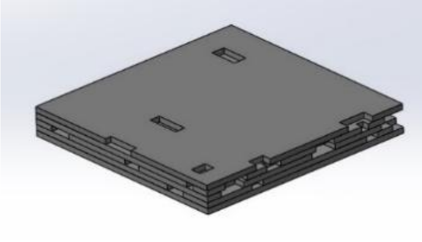

Fig. 7. **Modified (compacted) voxel model of the powder layer after fractal correction**

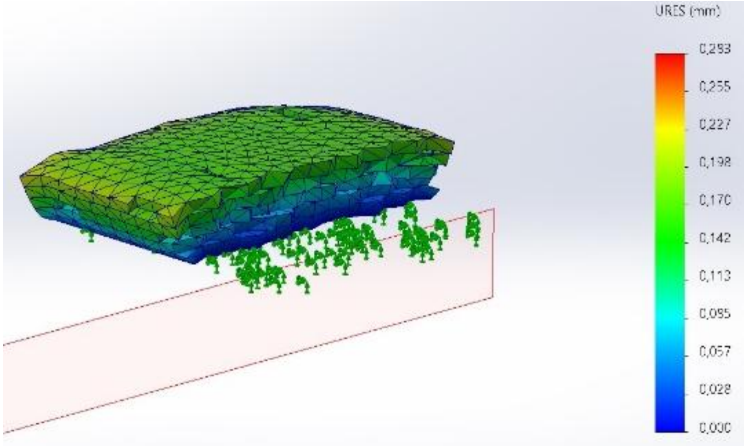

Fig. 8. **Stress–strain state (displacement) analysis of the modified voxel powder-layer model in SolidWorks Simulation**

Thus, the simulation experiments confirm that optimising the fractal characteristics of the layer through pre-compaction (e.g., via piezo-vibration) makes it possible to substantially improve the thermal regime and reduce residual stresses in SLS-printed parts. In this context, fractal analysis serves not only as a diagnostic but also as a corrective tool that can be integrated into adaptive control systems to improve the print quality in real time.

Conclusions

1. A method was developed for determining the combined fractal parameters (the fractal characteristic) of a powder layer by “stratifying” its voxel model. This made it possible to establish quantitative relationships between fractal dimension, void clustering, and heat-transfer efficiency within the layer, thereby enabling a more accurate assessment of the structural density of particle packing.
2. Simulation-based voxel models confirmed the critical influence of the powder morphology and void clustering on the thermomechanical parameters of SLS-printed parts. Optimal characteristics are achieved at a fractal dimension of $D_n^3 \approx 2.8$-2.9 and a clustering index of $P_k \leq 0.16$, which ensures a sufficient level of thermal conductivity and a reduction in residual stresses.
3. A method for print-quality control was proposed based on compaction of the powder layer (piezo-vibration simulation), which increases fractal dimension, decreases clustering, and optimises the

thermal profile. This reduces residual deformations by 17% and provides a basis for developing an adaptive feedback control system during the SLS printing process.

Author contributions

Conceptualisation – S.P.; methodology – S.P. and V.S.; software – S.P. and V.S.; validation – Y.B. and I.G.; formal analysis – M.T., N.T. and I.G.; investigation – S.P. and V.S.; data curation – M.T., N.T. and I.G.; writing – original draft preparation – S.P.; writing – review and editing – V.S. and Y.B.; visualisation – S.P. and I.G.; project administration – V.S., M.T. and N.T.; funding acquisition – Y.B., M.T., N.T., and I.G. All authors have read and agreed to the published version of the manuscript.

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