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Predictive Modelling of Surface Roughness in Layered Manufacturing Using H15N5D4B and KH28M6

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Abstract. Layered manufacturing (LM) technology has the capability to fabricate 3D physical models efficiently, overcoming the limitations of geometric complexities. However, the surface quality of LM-processed parts often falls short compared to parts made through traditional numerically controlled manufacturing technology. This issue of surface roughness has become a significant concern, despite the numerous potential advantages offered by LM. To address this, an elaborate methodology is proposed to predict the surface roughness of LM-processed parts. The proposed methodology takes into account both theoretical and real-world characteristics of surface roughness distributions to accurately reflect the actual roughness distributions in the predictions. This methodology was tested and used to evaluate properties of the H15N5D4B and KH28M6 materials. To achieve this, a design of the testing sample was developed, and a roughness distribution expression was introduced, utilizing measured roughness data from the aforementioned sample. This expression allows engineers to obtain surface roughness values for all surface angles, i.e., desired 3D models. The methodology also includes a prediction application, which demonstrates the validity and effectiveness of the proposed approach through several application examples.

1 Introduction

In the context of additive mass production, various challenges arise, such as linear dimensional deviations, discrepancies in shape and location tolerances, unforeseen porosity, possible cleavage, and discrepancies between the particle size distribution of metal powder compositions. Currently, the quality of parts produced using additive manufacturing relies on iterative trial-and-error approaches. These involve adjusting parameters to achieve the desired quality, specifically surface roughness, with a specified level of accuracy.

Regarding the materials used in additive manufacturing, stainless steel powders, particularly H15N5D4B (or its international analog ISO 5832-4) and KH28M6, are gaining traction for various uses, including aeronautical applications. This is largely due to their

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appreciable strength-to-weight ratio, impressive performance at high temperatures, and corrosion resistance. Surface roughness, a common parameter used to assess surface quality, is known to be significantly higher in AM products compared to those fabricated using traditional machining processes. Furthermore, the geometric attributes of the fabricated part, such as the angle of inclination, also affect its surface roughness. Due to the layered structure of powder bed technologies, a stair-step effect occurs, which significantly influences the surface roughness measured perpendicular to the steps [1-3]. Therefore, it is crucial to find analytical dependencies that will help predict and evaluate surface roughness due to its orientation.

Post-processing and surface treatments, such as machining, grinding, blasting, and electropolishing, are typically employed to minimize the surface roughness of AM parts. However, blasting, which involves the use of a jet of abrasive particles (usually corundum or glass microspheres) against a surface using controlled pressure, is the most common method used to decrease the surface roughness of built samples and to enhance mechanical properties. For obtaining high-quality, bright surfaces, electropolishing is typically applied [4-5].

The combined benefits of blasting and electropolishing have been previously acknowledged [6-11]. However, the ability to predict the raw roughness of a part before these processes has been largely overlooked in existing literature [12]. Therefore, the authors propose a methodology that takes into account both theoretical and real-world characteristics of surface roughness distributions, surface angle distribution, and the formation of the up-skin/down-skin layers

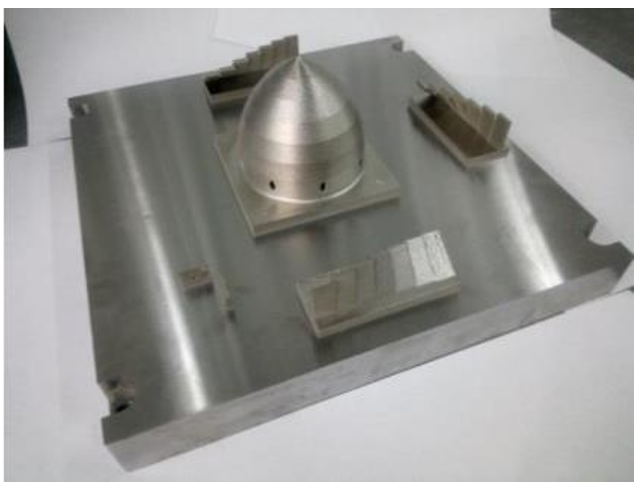

Fig. 1. Design of the test sample.

2 Methodology

To find relationships among surface roughness parameters (Ra, Rz), the surface incline angle relative to the recoater, and the angle between the building platform and examined surface, a test sample was developed (see figure 1). [12-13] The print modes of the test sample are listed in the table. During the printing process, ISO 5832-4 material was selected for stability, P refers to power, V indicates speed (in mm/s), and layer height is represented by h (in mm).

Table 1. Printing parameters

Material		KH28M6			H15N5D4B	
Layer thickness, μm		20	40	50	20	40
Infill	Laser power, W	195	290	310	195	220
	Laser speed, mm/s	800	950	1000	1000	755
Up-skin	Laser power, W	195	180	190	195	74
	Laser speed, mm/s	800	650	650	1000	951
Down-skin	Laser power, W	195	140	145	195	180
	Laser speed, mm/s	3000	2400	2000	2700	654
Contour	Laser power, W	120	190	200	80	135
	Laser speed, mm/s	800	400	400	1600	365

The geometry of the test sample is similar to the surface of a cone, which ensures that it can be printed without collapse and synthesized without the need for support structures. [14] The authors of this study are focused on evaluating and predicting the raw surface of the synthesized part. [15] The sample has a wall thickness of $\delta = 2\,mm$. According to the GOST 2789-73 methodology, the roughness of the outer and inner parts was measured; the printed parts were cut into four equal pieces (see figure 2). The sample was cut using the electro-erosion method. Measurements were taken on the profilometer HOMMEL TESTER T8000 with sections (up-skin, down-skin) of the sample at an angle of inclination of the surface relative to the original structure, ranging from 30° to 90°, within a range of 10°, and after 30° relative to the direction of the knife's movement. The angle interval was selected based on practical experience. [16]

The same measurements were performed for the cobalt alloy KH28M6. Based on the measurement results, graphical dependencies of the roughness values on the angle of rotation relative to the knife and the angle of inclination of the surface relative to the construction plane were plotted. The analysis of these graphs showed that in a double logarithmic coordinate system, the relationship between Ra and the angle of inclination of the surface relative to the construction plane α takes the following form [17]:

$$Ra = C \cdot \alpha^{-x}.$$

3 Results and Discussion

Based on the measurements of the roughness parameters, the dependences of Ra on the angles of the position of the surface relative to the knife α and the slope of the surface relative to the construction plane φ are plotted.

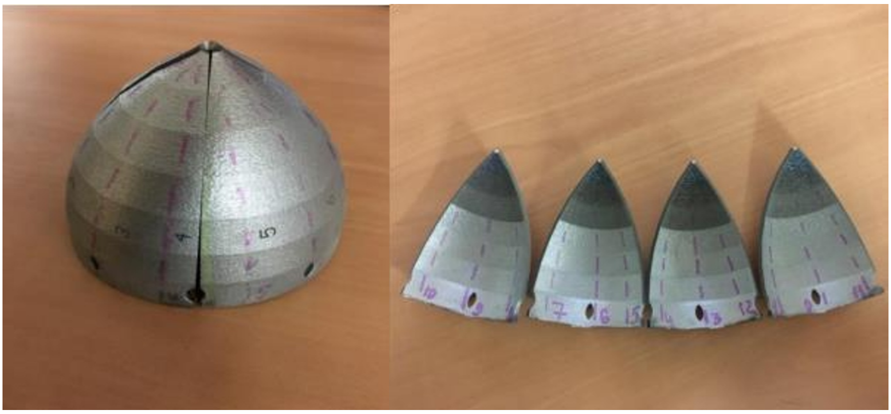

Fig. 2. Printed and cut parts.

Table 2. Experimentally obtained values of the parameters C, x.

The angle of rotation of the surface relative to the movement of the knife, $\varphi°$	C	x
0	0,1265	0,8851
30	0,9082	0,5102
60	3,7038	0,1176
90	2,2181	0,2548
120	2,6081	0,1947
150	3,4218	0,1540
180	3,9425	0,1339
210	0,7128	0,4944
240	0,2052	0,7515
270	1,3916	0,2703
300	0,4176	0,5182
330	0,219	0,6825

The analysis of the above graphs showed that in the double logarithmic coordinate system, the relationship between Ra and the angle of inclination of the surface relative to the construction plane α has the following form

$$Ra = C \cdot \alpha^{-x}.$$

The values of the parameters C and x for surfaces with different angles of rotation relative to the knife φ, with its values from 0° to 360°, are different. Based on the data given in the table No. values C and x depending on the angle view

$$C = C_1 \cdot \varphi^{x_1}$$
$$x = C_2 \cdot \varphi^{x_2},$$

and the formula for determining the roughness parameter Ra for the outer surface is:

$$Ra = 36.932 \cdot \varphi^{-0.694} \cdot \alpha^{0.0722\varphi^{0.2892}},$$

and for inner surface:

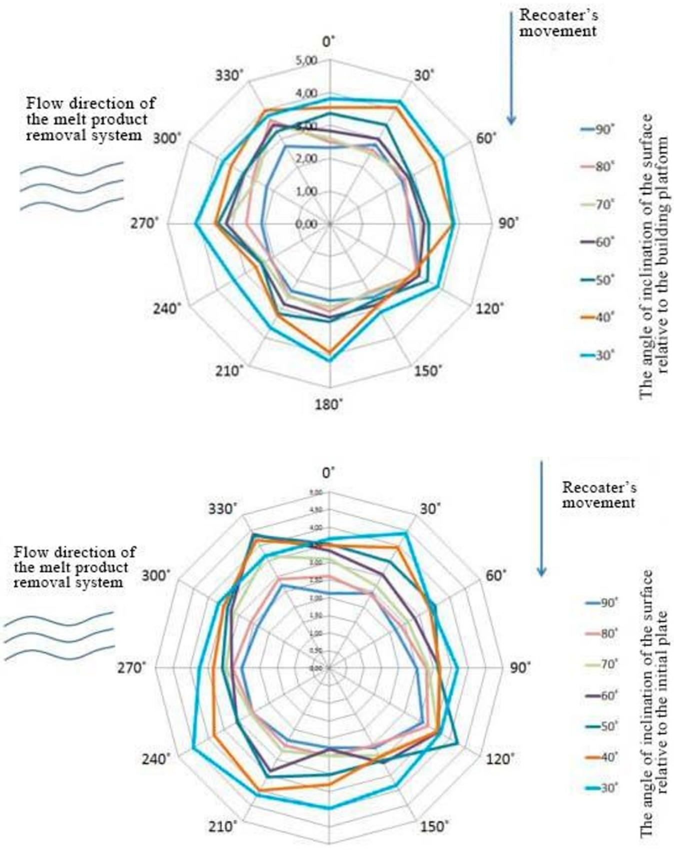

Fig. 3. Surface roughness of samples. a) up-skin surface, b) down-skin surface.

$$Ra = 5.6643 \cdot \varphi^{0.3881} \cdot \alpha^{-0.2055\varphi^{0.1415}}.$$

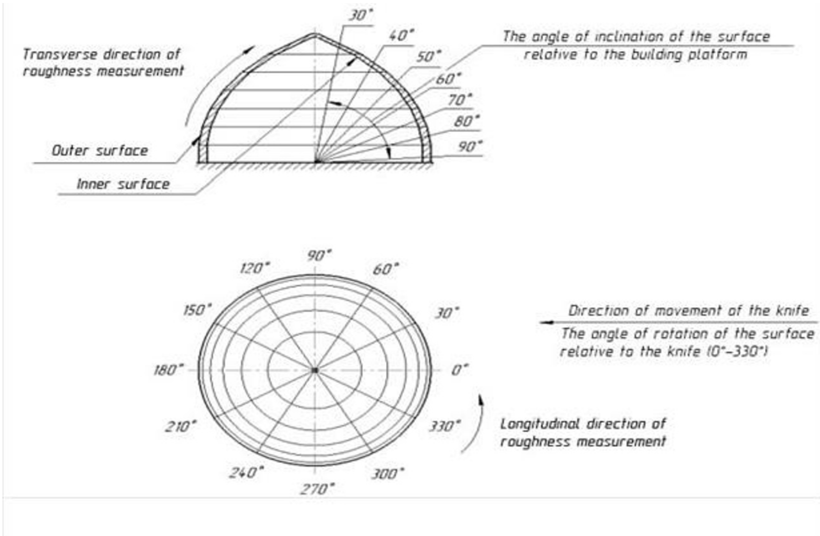

Fig. 4. Test sample and conducted measurements.

Similarly, to how it was done for the H15N5D4B material dependencies for the KH28M6 were obtained and calculated in order to determine the value of Ra in the printed part:

outer surface:

$$Ra = 0.4672 \cdot \varphi^{-0.22} \cdot \alpha^{0.2747\varphi^{0.1577}},$$

inner surface:

$$Ra = 23521 \cdot \varphi^{-0.763} \cdot \alpha^{-3.5559\varphi^{-0.288}}.$$

Table 3. Comparison of the calculated and experimental Ra values of H15N5D4B material.

The angle of rotation of the surface relative to the movement of the knife, $\varphi°$	Angle of inclination of the surface relative to the construction plane	Estimated value, μm	Measured value, μm	Difference, %
Outer surface				
60	30	1,128	1,3	19,2
120	50	1,603	1,9	15,6
180	70	2,103	3,0	47,2
240	80	2,435	3,2	23,9
330	90	2,852	2,7	5,6
Inner surface				
90	60	5,09	3,3	78,8
150	70	5,347	3,1	72,5
210	80	5,026	3,2	57
270	90	4,925	3,0	64

There is also a high level of instability of roughness indicators, especially for the inner surface.

4 Conclusions

A technique was developed, and test samples were printed. This allowed, based on the results of the obtained experimental data, the connection between the roughness parameters and the angles of inclination of the part's surfaces relative to the construction platform and the recorder to be established. Also:

1. The calculated dependencies presented in this article for determining roughness parameters can be used by designers when assigning surface quality parameters during product design, as well as by technologists when developing technological processes for manufacturing parts.
2. It has also been established that with a change in the thickness of the alloyed layer in the range from 20 to 40 μm, the values of the roughness parameters change insignificantly. The fluctuation in the roughness parameter values ranges from 7.7% to 10%.
3. According to the provided tabular data (table 4), the discrepancy between the Ra values obtained by calculation and the actual values is less for the outer surface than for the inner one. That is, the outer surface roughness is more stable.

4. Based on the processing of experimental data, it was found that the ratio of Ra to Rz on parts obtained by laser additive sintering is 1/6, which slightly differs from the ratio established by GOST 2789-59 [26-32]. This confirms the possibility of assessing the roughness of such parts in accordance with this standard."

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