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Surface Anisotropy on 3D Printed Parts

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Abstract
It is well known that the surface quality obtained in additive manufacturing processes is highly variable. There are several reasons for this, of which the most prominent is the staircase effect, which results from the fact that 3D printing can be actually considered as a 2.5 machining process, as we build the part layer by layer. However, this staircase effect can be very different on surfaces that are arranged in different ways. By measuring the values that characterise the surfaces (R_a, R_z), however, we can observe that they are direction dependent, i.e. it does not matter how we measure them. This phenomenon is called surface anisotropy. It is clear that the surface roughness also has an effect on the tribological behaviour. In the case of a component where it is in contact with another component and relative displacement occurs between them, frictional properties may play a prominent role, which may thus also become direction dependent. Surface roughness also has a clear effect on fatigue properties. Consequently, for parts undergoing periodic dynamic stresses, it may be important to choose the right manufacturing orientation. The present study aims to demonstrate the extent of variation in surface roughness on different surfaces of a part produced by FDM. For this purpose, surface quality factors are investigated and evaluated on a self-designed model produced with given manufacturing parameters.

Keywords
surface anisotropy, surface roughness, additive manufacturing, FDM

1 Introduction

The requirements of Industry 4.0 often demand the production of customised or small series products within a short timeframe. In such cases, additive manufacturing technologies are often the only option. However, like all manufacturing technologies, 3D printing has its own specificities. The most typical characteristic of additive manufacturing technologies is the so-called staircase effect, which results from layer-by-layer build-up [1]. The resulting parts' behaviour under load can be described by an anisotropic material model [2]. This topic has been studied extensively. However, the layers remain mostly detectable on the side surfaces of the parts due to the layered construction [3, 4]. In many cases, a finished product is produced directly using this method, so we expect a good surface quality. This is to replace, for example, injection moulding, which requires considerable design, tooling and cost [5]. However, it is important to note that the surface quality achievable is influenced by the manufacturing methods and parameters [6–8]. There are options for post-processing, of course. One commonly used solution is machining to produce a final surface with precision and adequate roughness [9–11]. Another increasingly common technique is coating [12]. The investigation of the effects of this is ongoing, for example, in relation to customised implants [13]. Another method for enhancing surface quality is to rescan the top layer without adding any material [14–16]. Changes in surface quality can affect the mechanical properties [17–21]. Additionally, surface quality significantly influences tribological properties [22–24]. The current study investigates the extent of surface anisotropy by demonstrating it on a test specimen of concrete.

2 Methodology

As stated in the introduction, the surface quality of additively manufactured parts depends on various factors. It has been demonstrated that there are numerous methods available to modify surface roughness afterwards. This study focuses on investigating the surface quality of a single part without post-processing, which is the result of manufacturing, by determining the surface roughness characteristic which is accepted in mechanical engineering.

Fig. 1 displays the geometric design of the test specimen, which I developed to allow me to test multiple surfaces in different positions.

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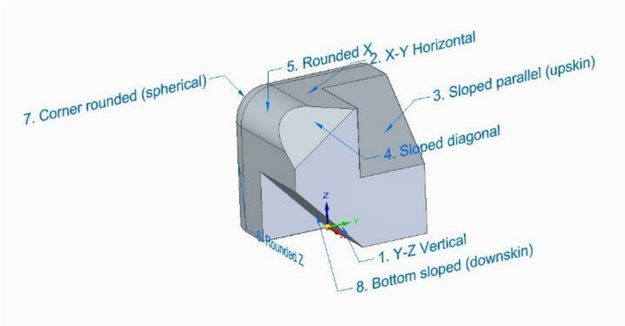

Fig. 1 The specimen used for the investigation

It is evident that the marked surfaces will have varying degrees of surface roughness. The impact of the staircase effect is already visible in the slicing software (toolpath generation) (Fig. 2).

There are two main methods for testing surface roughness. In the past, the contact method has been used, where a needle is drawn in a straight line along the surface and its displacements are magnified to obtain the so-called detected profile. Today, microscopic testing is becoming more common. This method involves scanning the surfaces to be examined and taking measurements in software. The results of the microscopic examination are presented in this study, which was carried out using a Keyence VR-5200 microscope.

The Keyence VR-5200 series uses a white LED light source for its structured light projection. White light contains a broad spectrum of wavelengths, which helps in capturing detailed surface information and achieving high-resolution measurements.

Using white light, Keyence creates a 3D profile that is evaluated by software. In this case, the laser wavelength has no effect on the measurement results. If it were used as a direct optical microscope to measure surface roughness, the wavelength would be important. Different materials (metal, plastic, glass) and surface finishes (matte, glossy, rough) require different illumination settings for optimal measurement accuracy. Keyence laser scanners have automatic calibration functions to adjust the laser power and optimize measurement conditions based on the surface being measured.

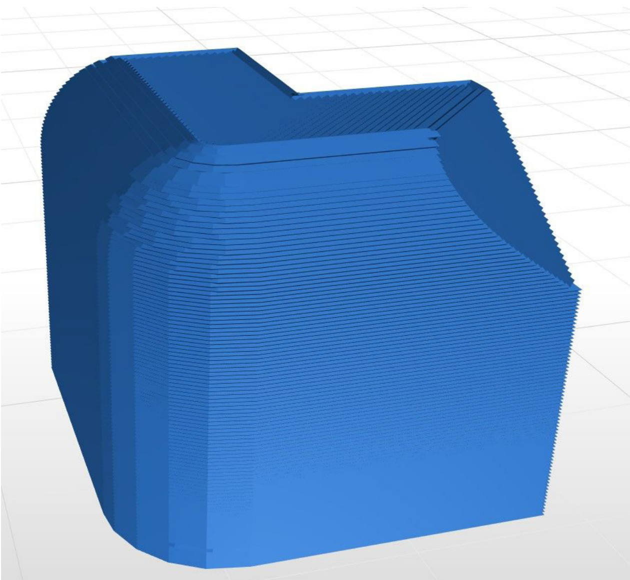

Fig. 2 Design of toolpath

This test focuses on only one surface and aims to demonstrate the anisotropic nature of the surface. As a first step in the investigation, we scanned the surface under investigation, as shown in Fig. 3.

In Fig. 3, the layering resulting from the manufacturing technology is clearly visible. This indicates that the surface roughness may vary in different directions, even within the same surface. The test was conducted following ISO 4287:1997 [25], which defines surface roughness.

To determine the differences, a complex examination was carried out on a selected surface, both in the vertical and horizontal directions, and in a new way that is only available with the microscopic method. Basically, the idea and definition has been that the roughness should be measured perpendicular to the direction of the grooves, but since the surface roughness affects the tribological and mechanical properties, it is useful to map the surface thoroughly. Furthermore, when considering tribological properties, it is common practice to work with relative displacements, and the direction of these displacements can be crucial. The test involved comparing not just one curve, but a series of parallel curves. To achieve this, it was necessary to define the initial line, as well as the distance and number of curves. This approach ensures that profiles that are not well-defined on the surface are not accidentally examined, which could lead to false conclusions. A further advantage is that statistical analyses can be conducted, which also provide insight into the consistency of the surface quality.

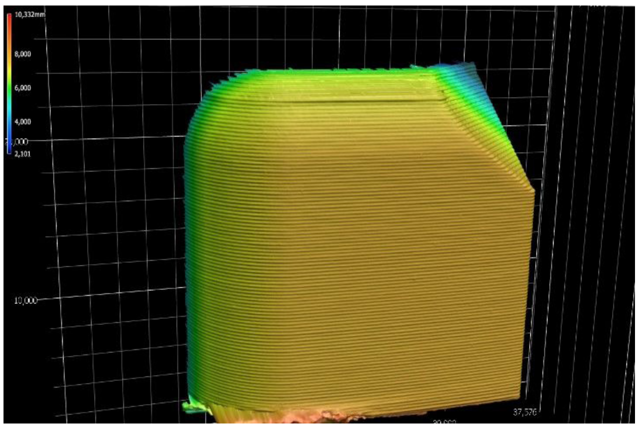

Fig. 3 Scanned image of test surface

3 Results

3.1 Vertical

Fig. 4 illustrates a straight base profile taken in the vertical direction and a 5-5 profile taken parallel to it in both directions.

The direction perpendicular to the layers and grooves is defined in the Fig. 4. The resulting average roughness profile is shown in Fig. 5.

The measured results are given in Table 1, where R_a is the average roughness, R_z is the roughness height, R_q is the roughness variance, R_{sk} is the skewness and R_{ku} is the kurtosis of the roughnesses.

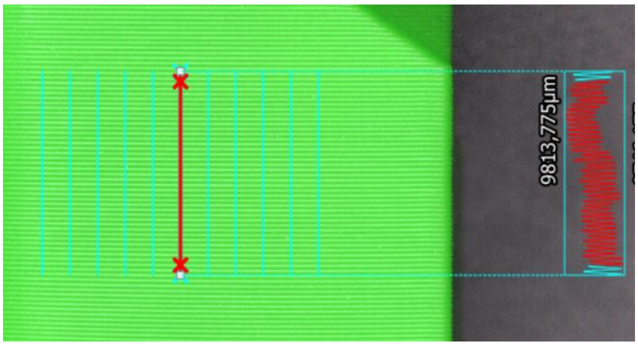

Fig. 4 Vertical profiles

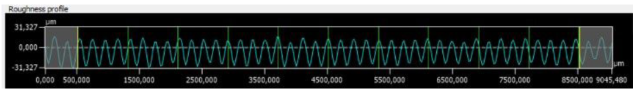

Fig. 5 Average roughness curve of vertical profile

Table 1 Roughness parameters measured in the vertical direction and their statistical characteristics

	R_a	R_z	R_q	R_{sk}	R_{ku}	Evaluation length
Unit	µm	µm	µm			µm
Ave.	11.933	40.657	13.341	−0.088	1.567	
Max.	12.564	43.710	14.053	−0.024	1.598	
Min.	11.489	39.047	12.833	−0.134	1.552	
Std. DV	0.318	1.344	0.358	0.030	0.013	
Line 1	11.489	39.550	12.833	−0.071	1.578	6442.986
Line 2	12.147	41.869	13.608	−0.077	1.568	6442.986
Line 3	12.050	40.661	13.461	−0.101	1.552	6442.986
Line 4	11.571	39.047	12.922	−0.121	1.555	6442.986
Line 5	11.614	39.569	13.003	−0.134	1.581	6442.986
Line 6	11.718	39.846	13.129	−0.103	1.570	6442.986
Line 7	11.750	39.213	13.124	−0.114	1.561	6442.986
Line 8	11.962	40.926	13.339	−0.097	1.564	6442.986
Line 9	12.196	41.647	13.627	−0.066	1.561	6442.986
Line 10	12.207	41.189	13.654	−0.064	1.555	6442.986
Line 11	12.564	43.710	14.053	−0.024	1.598	6442.986

3.2. Horizontal

Fig. 6 illustrates a horizontal linear base profile and parallel 5-5 profiles in both directions.

Fig. 6 shows that for measurements with this orientation, the profile lines run along the edges of the grooves and in the valleys between or parallel to them. The average roughness profile obtained is shown in Fig. 7.

Table 2 presents the statistical characteristics and results measured horizontally.

3.3 Surface (Area)

After measuring the roughness along the horizontal and vertical line profiles, I also examined the roughness parameters on a given area. Fig. 8 shows the surface under investigation, on the same side of the specimen where the horizontal and vertical lines were recorded.

In this case, we analysed the roughness parameters at each point of the considered area. The results are summarised in Table 3, where S_a represents the average roughness, S_z represents the roughness height, S_q represents the roughness variance, S_{sk} represents the skewness, and S_{ku} represents the kurtosis of the roughness.

3.3.1 Angular spectrum

The surface structure's orientation is clearly visible, as demonstrated in Fig. 9.

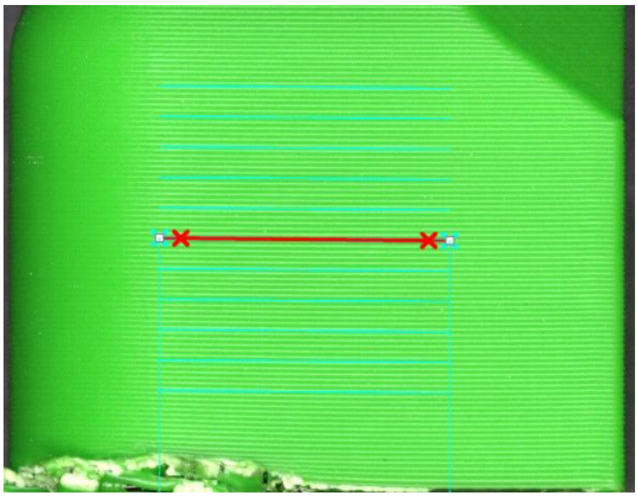

Fig. 6 Horizontal profiles

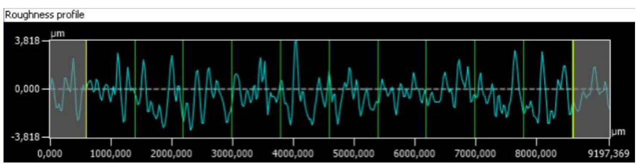

Fig. 7 Average roughness curve of horizontal profile

Table 2 Roughness parameters measured in the horizontal direction and their statistical characteristics

	R_a	R_z	R_q	R_{sk}	R_{ku}	Evaluation length
Unit	μm	μm	μm			μm
Ave.	0.789	4.285	1.029	0.666	3.732	
Max.	0.955	5.082	1.207	1.187	4.843	
Min.	0.478	2.988	0.684	0.179	2.559	
Std. DV	0.129	0.558	0.143	0.319	0.763	
Line 1	0.680	4.011	0.919	1.187	4.644	8803.527
Line 2	0.866	4.143	1.066	0.179	2.559	8803.527
Line 3	0.811	4.481	1.052	0.756	3.991	8803.527
Line 4	0.906	4.576	1.145	0.409	3.039	8803.527
Line 5	0.869	4.750	1.143	1.116	3.920	8803.527
Line 6	0.659	3.670	0.869	0.792	4.055	8803.527
Line 7	0.835	4.131	1.048	0.371	2.791	8803.527
Line 8	0.774	4.686	1.079	0.912	4.843	8803.527
Line 9	0.841	4.617	1.104	0.691	3.648	8803.527
Line 10	0.478	2.988	0.684	0.657	4.612	8803.527
Line 11	0.955	5.082	1.207	0.258	2.951	8803.527

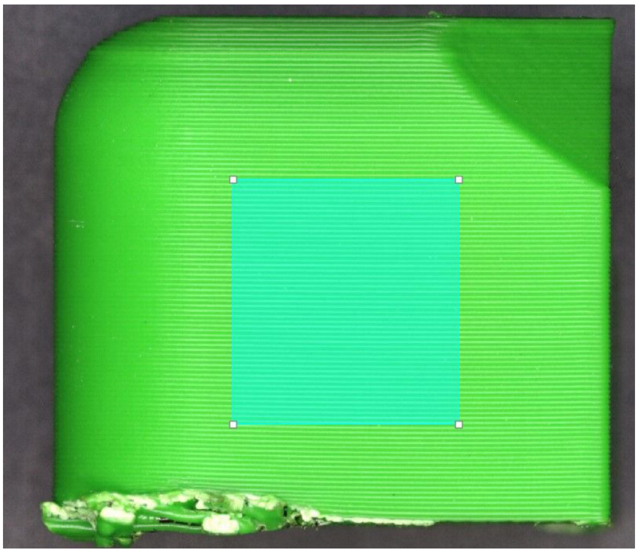

Fig. 8 Area for surface roughness testing

Table 3 Roughness parameters measured on a given area and their statistical characteristics

	S_a	S_z	S_q	S_{sk}	S_{ku}	Area size
	μm	μm	μm			μm²
Area1	13.02	81.763	14.622	−0.103	1.611	85693700

4 Analysis

Examining the results by comparing the horizontal and vertical directions, we see that there are significant

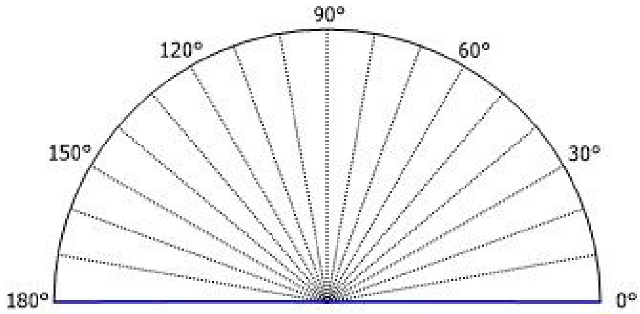

Fig. 9 Angular spectrum of the investigated surface

differences as a function of orientation, as we expected. The average roughness measured in the vertical direction was R_a = 11.93 μm, whereas in the horizontal direction, the average value was R_a = 0.79 μm.

Regarding the vertical direction, the obtained values are only slightly displaced from the mean value (R_{sk} = −0.09). The kurtosis values (R_{ku} = 1.57) indicate that the measured values in this direction are relatively uniform and not very close to the mean value.

In the horizontal direction (parallel to the layers), the average surface roughness measurements deviate significantly from the mean value (R_{sk} = 0.67). Additionally, the majority of the measured values are in the immediate environment of the mean value, as indicated by the kurtosis value (R_{ku} = 3.73).

In terms of the roughness measured on the area, we can see that S_a = 13.02 μm, while the skewness is S_{sk} = −0.1 and the kurtosis is S_{ku} = 1.61, which means that most of the measured values are not in the immediate area where the mean value is. Fig. 9 also shows that the orientation of the surface structure is 0-180°.

5 Conclusion

A notable contrast is evident between the two principal directions of roughness, horizontal, parallel to the layers, and vertical, perpendicular to the layers. Fig. 10 illustrates the measured curves in the different directions.

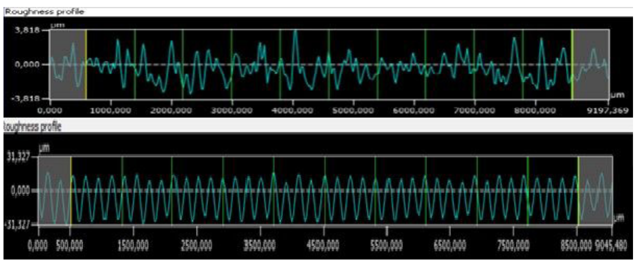

Fig. 10 Average roughness curve of horizontal (top) and vertical (bottom) profile lines

The Fig. 10 clearly demonstrates that the values and the characteristics of the values of the different roughness types vary significantly. This suggests that the surface under investigation is an anisotropic surface.

It has been observed that the roughness values measured on the area, both in value (R_a–S_a) and in character (R_{ku}–S_{ku}), are similar to those measured vertically (in the direction perpendicular to the groove direction, perpendicular to the layers).

6 Summary

To summarise, the layer-by-layer build-up inherent to additive manufacturing technology results in the characteristic material properties and surface anisotropy of the resulting parts, the extent of which is significantly influenced by the manufacturing technology parameters. Surface roughness affects tribological and mechanical properties, so it is important to map the main orientations in the surface structure to reduce friction and wear. While the mechanical design it must take this into account to the material properties, there are a number of post-processing and surface coating technique that can be used to improve surface roughness.

The study indicates that there can be a significant difference in surface roughness between the directions perpendicular to and in the direction of building. Therefore, it is concluded that non-machined 3D printed parts should be considered anisotropic in terms of surface roughness.

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