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SURFACE MODIFICATION METHODS OF PLASTIC COMPONENTS PRODUCED BY ADDITIVE MANUFACTURING: A REVIEW

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Abstract: Additive manufacturing (AM) is a widely used process today, especially for the production of complex parts that cannot be produced with traditional material removal technologies. However, in the case of components produced by 3D printing, due to the specifics of the technology, poor surface quality is often to be expected. From the point of view of the product and production process, the so-called textural characteristics, surface roughness can be considered the most critical component. The surface of the part produced by 3D printing must meet several criteria (e.g., mechanical, physical, tribological, aesthetic, etc.). This article discusses the possibilities of surface modification of polymer parts produced with additive manufacturing technology, focusing on their effects on surface roughness. The paper also deals with the features suitable for describing the surface texture of 3D printed parts and their role in the characterization of printed parts.

Keywords: *surface treatment, plastic, additive manufacturing, surface roughness*

1. INTRODUCTION

Nowadays, polymer-based materials (Kmetz & Takács, 2020) are successfully used in many industrial fields, and they can replace metal, - and ceramic materials in an increasing proportion in several sectors, starting from electronics to the food industry, up to the car, - and aircraft industry (Tuazon, Custodio, Basuel, Reyes, & Dizon, 2022), (Lim, Le, Lu, & Wong, 2016), (Elakkad, 2019), (Raheem, 2012).
The use of high-performance technical plastics in the automotive industry is constantly increasing, thanks to their favourable properties, such as their chemical

inertness, mechanical properties, economical production, and the ability to be extensively modified with additives (Patil, Patel, & Purohit, 2017), (Kim, et al., 2023), (Sadiku & Ibrahim, 2007). The surface properties of polymers often do not meet the requirements for scratch resistance, wettability, adhesive behaviour, and friction. For this reason, additional surface treatments are often required to achieve the desired properties while maintaining the characteristics of the volume. A possible grouping of surface treatment methods is illustrated in Figure 1.

Surface modifications of polymers can basically be classified into two groups: procedures involving the addition of material and procedures involving the removal of material. Processes involving the addition of material are the various coating processes (e.g., PVD, CVD), which can improve wear resistance, powder spraying (Heinze, Menning, & Paller, 1995), (Medel, et al., 2010).

It is also possible to influence the surface roughness without adding any material. Etching, for example, can be considered such a treatment. In these cases, the etchant used during etching mostly means acids and alkalis that are solvents for the polymer itself. In the case of polylactic acid (PLA), which is most often used during additive processing, NaOH can be such an etchant: Schneider (Schneider, et al., 2020) highlighted during his research that in the case of PLA printed parts, increasing the milling time causes an increase in surface roughness. At the same time, it can also be observed that the surface roughness of the printed material is initially smaller, on average 4.5 nm, but after a four-hour treatment, this increases to about 160 nm, thanks to erosion.

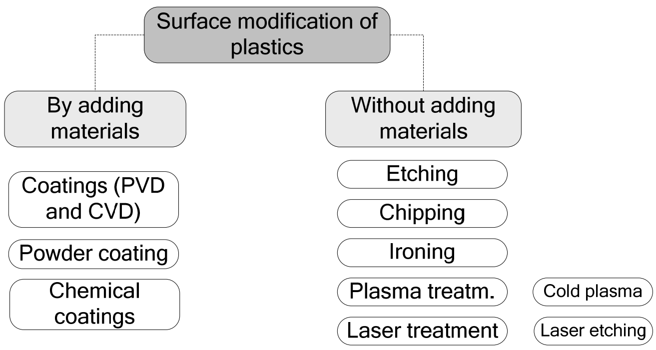

Figure 1. *Classification of surface modification technologies in case of AM plastic part*

Mechanical surface modifications include sanding, abrasive treatments, and barrel finishing. CNC milling is also widely used to improve surface roughness, which can be used well for simple geometries, but less so for undercut parts. chemical treatments are widely used, due to their many advantages, such as the absence of geometrical limitations and the speed of the process, but at the same time, the harmful effects of chemicals (e.g., health-damaging or toxic fumes) must be taken into account.

According to the relevant literature, in the case of polymers, surface and bulk eroding material types can be distinguished. Figure 2 illustrates the differences between each type of erosion.

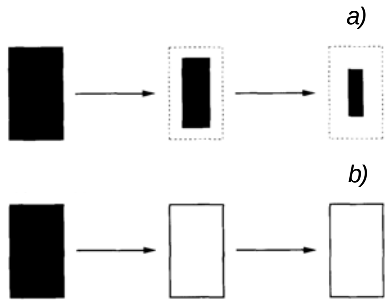

Figure 2. *Schematic diagram of the process of bulk and surface erosion a) surface b) bulk erosion (Schneider, et al., 2020)*

In the case of surface erosion, material loss occurs only from the surface of the polymer during a given application. In this case, a decrease in size can be observed, but at the same time they retain their original geometric shape. (On the other hand, during bulk erosion, the erosion is not only limited to the surface.)

2. Surface roughness and AM

The surface texture of a part produced by 3D printing can be described with several components, such as waviness, profile, and surface roughness (Figure 3). The individual components and their reasons and explanations are summarized in Table 1. (Golhin, Tonello, Frisvad, Grammatikos, & Strandlie, 2023).

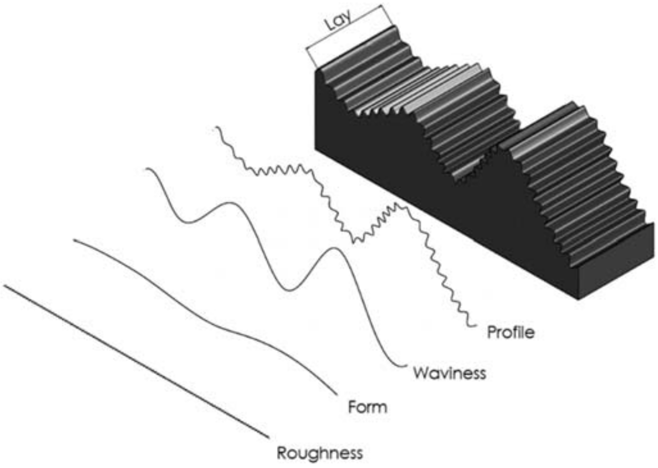

Figure 3. *Texture components of 3D manufactured parts (Golhin, Tonello, Frisvad, Grammatikos, & Strandlie, 2023)*

Table 1.
Texture components and interpretation of AM parts (Golhin, Tonello, Frisvad, Grammatikos, & Strandlie, 2023)

Texture component	Reason/Interpretation
Profile	can be ascribed to layer-by-layer manufacturing
Waviness	Machine vibration; Poor adhesion of layer; Thermal distortion; mechanical deformation during post-processing
Form	Poor performance of manufacturing system
Roughness	generated by surface irregularities due to printing and material removal errors

Among the components mentioned above, surface roughness can be considered the most critical component from the point of view of characterizing the texture. The surface roughness can most generally be described with the roughness parameter Ra, however, there are studies that indicate that the parameters Sa (average area surface) and Sq (area root mean squared height) may also be suitable for characterizing the surface roughness, since these parameters are less sensitive to the measurement conditions such as sampling and evaluation length.

3. SURFACE MODIFICATION METHODS WITHOUT MATERIAL ADDING

3.1. Plasma and laser treatments, etching

Cold plasma is the most suitable for surface modification of polymers (Károly, Klébert, & Kalácska, 2015), (Berczeli, Hatoss, & Kókai, 2022). In this case, the atoms are at room temperature, while the temperature of the electrons is much higher, even an order of magnitude higher. The high electron temperature also results in significant chemical reactivity, which is why it is well suited for the treatment of bulk materials and even parts produced by additive processing (Figure 4).

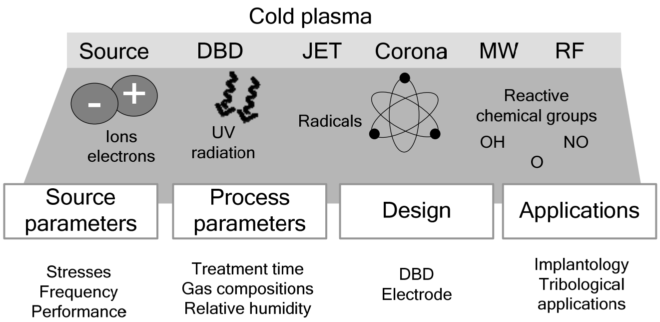

Figure 4. *Cold plasma treatment: process, parameters, and typical applications*

Several plasma sources can be used to create the plasma state, such as a corona discharge or a plasma beam.

The reduction of technological costs leads the development of plasma treatments in the direction of the use of cold plasma. There are many applications where low-pressure plasma cannot be substituted. Nevertheless, there are applications where the use of non-equilibrium cold plasma at atmospheric and higher pressures has significant advantages.

In their research, Károly et al. (Karoly, et al., 2019) investigated the effect of cold plasma treatment on the tribological and adhesion properties of PTFE and PA 66 materials. The treatment was carried out for periods of 24 and 800 h. Based on the tests carried out, it can be concluded that in the case of these materials, the cold plasma treatment influenced the surface composition, and the treatment resulted in oxidation of the surface. Tribological tests on various materials have shown that, under low and medium loads, PA has significantly higher wear resistance than PTFE.

Regarding the friction coefficient, it can be established that the treatment time affects its change. It can be observed that 24 h of plasma treatment results in a decrease in the coefficient of friction, while after 800 h the coefficient of friction increases.

Most literature uses the roughness parameter Ra to quantify the surface roughness, which does not consider the morphological characteristics of the surface, since profiles of different shapes but with the same arithmetic mean peak height and valley depth show the same Ra values. In terms of surface roughness, the roughness parameter Rq can best characterize the change in roughness since this parameter is much more sensitive to the presence of roughness peaks and valleys.

Based on the research carried out by Mandolfino (Mandolfino, Lertora, & Gambaro, 2014), it can be concluded that - in the case of PP - the roughness of the surface increased significantly because of the treatment. The phenomenon can be explained by changes in the mechanical properties of the joints.

The change in roughness can also be explained (Kostov, Nishime, Castro, & Toth, 2014) in the case of this treatment by the fact that the radicals in the plasma gas collide with the polymer chains in the uppermost layers, which can thus split. Chain scission can result in the formation of low molecular weight oligomers, which must be removed from the surface, thus influencing changes in surface topography. This so-called material removal process results in an effect similar to etching, which is responsible for the change in surface roughness.

During his research, Hegemann (Hegemann, Brunner, & Oehr, 2003) investigated the effects of plasma treatments on adhesion and surface characteristics in the case of PC and EPDM materials. In his research, he analysed the effect of reaction gases (He and Ar) on the friction coefficient. In his research, Hegemann discussed the friction coefficient at the atomic, micro, and macroscopic levels. Accordingly:

- the friction coefficient interpreted at the atomic level is based on dissipative mechanisms and can be defined as the sliding of atoms on each other.
- at the microscopic level, friction means the relative displacement of two interacting surfaces;
- at the macroscopic level, the friction factor is the ratio of the friction force and the load force.

During the examinations performed, the coefficient of friction of the various polymers under given test conditions (treatment parameters – 20 minutes treatment time, 300 W power and 0.2 mbar pressure) resulted in a reduction of the friction coefficient. Increasing the treatment time caused a further decrease in the friction factor. However, when the plasma treatment was performed 1 month later, it no longer caused a significant reduction in the friction factor.

Zhang (Zhang, Häger, Friedrich, Song, & Dong, 1995) plasma-treated PEEK, PEEK+8% PTFE, and PEEK+10% PTFE+10% carbon fibre materials to characterize the tribological properties. The treatments were performed in Ar gas, with treatment parameters controlled (treatment time: 1-5 minutes, voltage: 0.8-1.3 kV). The tribological tests were performed with a steel ring antibody. The tests carried out showed that the values of the sliding friction coefficient and the specific wear factor were significantly reduced, especially in the case of the PEEK-steel ring tribological pair. The average friction coefficient value

Decreased from 0.42 to 0.23. At the same time, in the case of samples that underwent plasma treatments, a different wear mechanism took place than in the case of untreated samples.

At the same time, the research points out that the plasma treatment can also affect the degree of crystallinity of the polymer, which can result in an increase in strength and hardness. This can be explained, among other things, by the presence of intermolecular binding forces in the crystalline phase, which lead to the formation of oriented chains (Balani, Verma, Agarwal, & Narayan, 2015).

One of the relatively new methods of improving surface quality is laser polishing, which - unlike traditional polishing processes - is more suitable for reducing the surface roughness of additively manufactured parts but does not involve component or tool wear (Mushtaq, Iqbal, Wang, Khan, & Petra, 2023).

By using laser technology, the Ra surface roughness can be reduced by up to 68-70% for PLA parts produced by FFF processing. With the help of continuous lasers, a constant and stable beam can be produced, with a constant power level, and therefore can also be used for cutting and welding. At the same time, with laser technologies – especially in the case of plastic parts – it must be considered that the beam (due to the longer exposure times) can cause thermal damage to the part. The solution can be the use of pulse lasers, which can be used to emit the beam with short pulses, with a higher peak value and a lower average power level. The short duration of the laser pulse enables a higher peak power to be achieved, without component failure caused by thermal damage.

During laser polishing (Figure 5), the laser beam is directed at the surface of the part, where it melts the material on a closed surface. The focal length affects the energy density and the amount of material removed, which determines the spot size. A smaller focal length results in a smaller spot size and a higher energy density, but at the same time results in less efficient material removal, which can cause an increase in the surface roughness Ra.

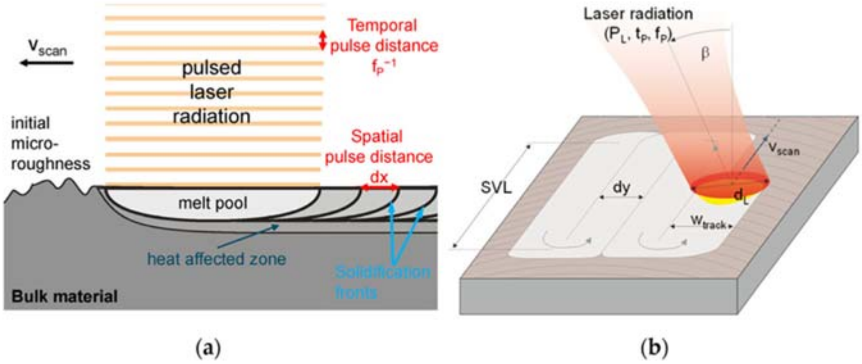

Figure 5. *Schematic illustration of laser polishing procedure a) pulsed laser operation with melt pool b) laser radiation (Mushtaq, Iqbal, Wang, Khan, & Petra, 2023)*

The surface quality and aesthetic appearance of plastic parts can be improved by laser polishing. At the same time, the technology is sensitive to the parameter settings, because incorrect settings can cause damage or destruction of the component due to the heat effect zone that occurs. Another problem can be the use of low beam energy, which results in the part being left untreated. During Mushtaq's research, he investigated the effect of laser polishing on the mechanical properties and surface quality of PLA parts produced by 3D printing. Based on the performed optimization experiments, it can be concluded that the mechanical properties (elastic modulus, tensile strength) can be significantly improved by determining the optimal laser scanning parameters (Mushtaq, Iqbal, Wang, Khan, & Petra, 2023).
Surface roughness can also be reduced with chemical treatments. The basis of the method is the choice of a chemical that is the solvent of the polymer to be treated. In the case of ABS, for example, dimethyl ketone-based solvents can be used with good efficiency to reduce roughness (Galantucci, Lavecchia, & Percoco, 2010). Lavecchia (Lavecchia, Guerra, & Galantucci, 2021) reduced the surface roughness of PLA parts produced with FFF technology by ethyl acetate treatment, the applied treatment time was 180 and 360 s. It can be concluded that even with a lower ethyl acetate concentration and a shorter treatment time, a significant (about 70%) reduction in roughness can be achieved, increasing the treatment time shows a significant decrease in the surface roughness values.

3.2. Roughness reduction with surface layers

Coating is a procedure often used to modify the surface roughness of bulk materials. The selection of the appropriate coating system depends on several parameters, such as the physical-chemical characteristics of the polymer, the porosity, surface characteristics and wetting ability of the bulk material (Zigon, Kariz, & Pavlic, 2020), (Khosravani, Zolfagharian, Jennings, & Reinicke, 2020), (Young, et al., 2016).
It should be noted that the coating of polymers –due to the specific properties of polymers (e.g., hydrophobic surface)– is only possible by using appropriate, mostly PU, acrylic or polyvinyl acetate based coatings (Zigon, Kariz, & Pavlic, 2020).
In their research, Zigon et al. (Zigon, Kariz, & Pavlic, 2020) investigated the effect of various coatings (waterborne acrylic coating – CW-B, solvent borne alkyd coating – CS-B and ABS diluted in acetone – C-ABS) on the surface roughness of ABS, PLA and PLA-W test specimens manufactured with FDM technology. was investigated. The individual test specimens were prepared by sanding to improve the adhesion of the coating. The test results of surface roughness measurements are presented in the following figure.

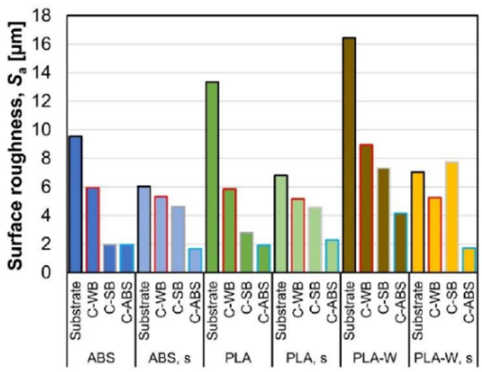

Figure 6. *Sa surface roughness parameters in case of different substrate materials (ABS, PLA and PLA-W) and coatings (CW-B, CS-B and C-ABS), s: sanded (Zigon, Kariz, & Pavlic, 2020)*

Based on the results of the surface roughness measurements, it can be concluded that the highest surface roughness can be observed in the case of the unpolished PLA-W specimens, while the smallest was determined in the case of ABS. It should be noted that both the layer thickness and the filling method have a significant effect on the surface roughness of 3D printed parts, while the printing speed does not affect it. By applying the CW-B coating, the surface roughness of the unpolished specimens decreased by about 50%, while the roughness reduction can also be observed in the case of the polished substrate, but to a much lesser extent (19%). In the case of the C-ABS coating, a 79% reduction in roughness can be observed, which can be explained, among other things, by the presence of the acetone solvent in the coating, which presumably also partially dissolved the substrate material. In general, surface roughness can be reduced with higher solids content coatings (Zigon, Kariz, & Pavlic, 2020).

In the case of polymers, a metal coating can also be detached on the surface by combining painting and laser treatment. In his research, Yung (Young, et al., 2016) developed a treatment method in which the surface of the 3D printed part is treated with malachite-containing acrylic paint, and then transformed into a copper layer by laser treatment, through photochemical processes. The structure of malachite is illustrated in Figure 7. In the molecule, the copper ions are connected only with oxygen ions. If the energy of the photon is high enough, copper (II) ions are split from the copper-oxygen bond and are transformed into copper (0) through homolysis.

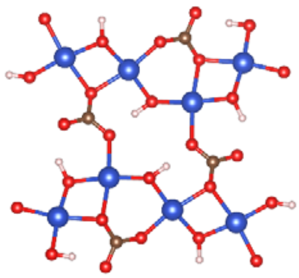

Figure 7. *Common structure of malachite (Crystallography 365, 2023)*

DLC (diamond like carbon) coatings are ceramic super hard coatings used for metallic materials, but they are also valid for polymer components to improve tribological performance (Marian, et al., 2023). The interpretation scheme of DLC coating is shown in Figure 8.

The DLC coating is a metastable form of amorphous carbon formed largely of sp3-hybrid carbon atoms,

The structure of DLC coating films moving from the substrate to the top of the coating, can be divided into three zones:

- the components of the surface substrates are mixed with carbon.
- the real DLC layer with sp3 bonds

– the more graphitic thin surface layer (Laszlo, 2021), (Bewilogua & Hofmann, 2014).

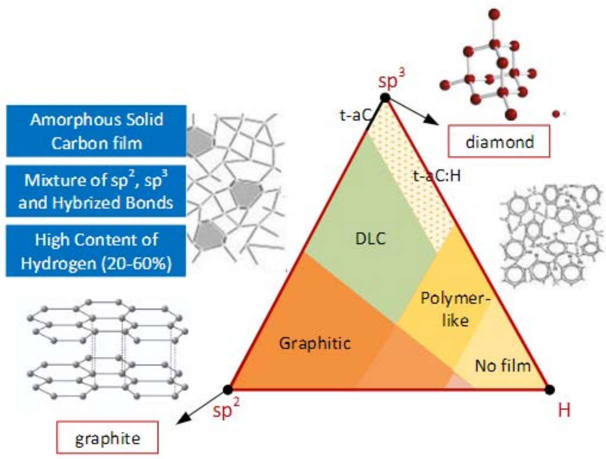

Figure 8. *Interpretation scheme of DLC coatings: amorphous carbon: a-C; amorphous carbon with tetrahedral structure: ta-C; amorphous carbon + hydrogen: a-C:H; tetrahedral amorphous carbon + hydrogen: ta-C:H (Casiraghi, Robertson, & Ferrari, 2007)*

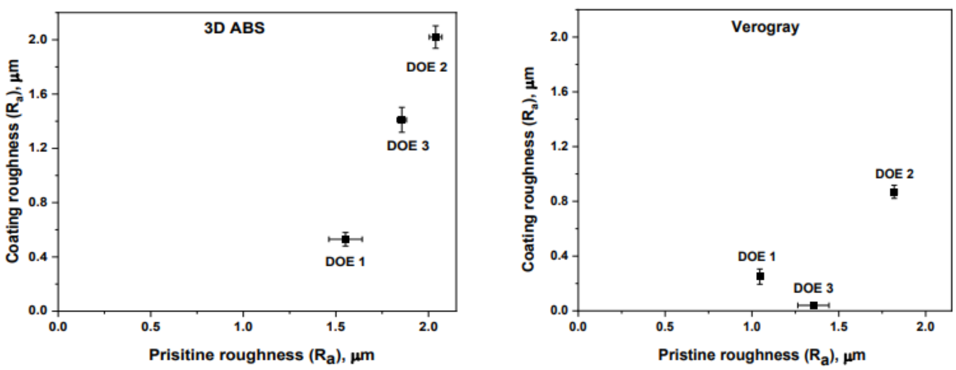

Figure 9. *Ra surface roughness of reference (uncoated) and coated ABS and Verogray 3D printed plastic parts (Ficzere, 2023)*

In the case of 3D printed parts exposed to wear, the friction conditions are determined by several parameters, such as hardness or surface roughness. During his research, Dangnan (Dangnan, 2021) dealt with the separation and testing of single-layer DLC coatings deposited by microwave-assisted PECVD process, in the case of ABS and Verogray (a type of modelling materials) material grades. In the case of the layers separated at a low temperature (45°C), in comparison with the surface roughness Ra of the reference substrate, a significant decrease in roughness can be observed in all cases. Figure 9 shows that the decrease in surface roughness is most significant in the case of ABS.

Depositing a surface layer without adding material during printing, so-called ironing is also possible. Ironing is a surface modification related to the printing process. The essence of the process is that after printing, the nozzle passes over the top layer - at the temperature used for printing - without adding material or with the addition of minimal material, because of which the surfaces merge better, the layer is more compact, the gaps are much better filled, while the surface roughness decreases (Ficzere, 2023).

Alzyod (Alzyod, Takács, & Ficzere, 2023) examined the effect of ironing post-processing on surface roughness, on specimens produced from PLA, using FDM technology, with regard to the examination of the effects of ironing parameters (ironing speed, ironing distance and volume flow). He investigated the determination of surface roughness using traditional, contact, and optical (non-contact) methods, and compared the results of these tests. The results show that the ironing process can lead to a significant reduction of the surface roughness, and that the surface roughness can be further reduced by optimizing the parameters.

4. Conclusion

The purpose of this research is to review the surface treatment and modification processes that help improve the surface quality of polymer parts, with regard to surface modifications suitable for reducing surface roughness.

In this paper, the most frequently used surface modification procedures and their most important characteristics were systematized and reviewed.

In addition to the conventional post-processing processes (e.g., cutting, grinding), various coating systems are now gaining ground, with the help of which not only the surface roughness can be reduced, but also –in the case of a given tribological system– the tribological performance of the part can be increased.

Although the individual treatments may already be suitable for reducing the surface roughness, in the future it may be advisable to calculate and examine the effect on the roughness by combining these procedures.

At the same time, it may also be worthwhile to deal with the quantitative characterization of surface roughness in the future: currently, most research examining the relationship between 3D printing and roughness characterizes the parts with the surface roughness Ra, however, this is a 2D characteristic that strongly depends on the test orientation used during the test (i.e., in which direction the measurement takes place on a given layer), a result closer to reality can be obtained by applying a 3D roughness measurement parameter.

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