UDC 667.629.83:502.131.1
Original Scientific Paper
https://doi.org/10.62598/JVA.11.1.6.17

Received: January 9, 2025
Accepted for publishing: June 16, 2025

TECHNICAL AND ECONOMIC ASPECTS IN THE DEVELOPMENT OF ADDITIVE TECHNOLOGY

Kostadin, Tihana, *Karlovac University of Applied Sciences, Croatia, tihana.kostadin@vuka.hr*

Šimunić, Nikola, *Karlovac University of Applied Sciences, Croatia, nikola.simunic@vuka.hr*

Feketić, Zvonimir, *Karlovac University of Applied Sciences, Croatia, zvonimir.feketic@gmail.com*

Abstract:
This paper studies the importance and development of additive technology through technical and economic aspects. The technical aspect includes research about the influence of surface inclination and layer thickness on the surface roughness of the produced test samples. Two AM technologies or processes (FDM and SLS) were used, with the use of three different materials (PLA, PETG and PA12) and two subsequent treatments (compressed air and glass bead blasting). Surface roughness parameters (R_a, R_z and R_{max}) were measured and analyzed after different manufacturing conditions. Their variability and statistical analysis are presented. From the obtained results, it is evident that with increasing slope (from 0° to 90°) the values increase to a maximum (between 10° and 40°), after which they decrease (from 50° to 90°), while increasing the thickness of the layer causes higher values of roughness parameters. Also, the aim of the paper is to determine the economic profitability of the used procedures, that is, the impact of the manufacturing procedures on the price of the product. Modern and innovative materials and technologies are used in the research. By using innovative technologies, we influence on sustainable development, which speaks of the fact that we need to meet our needs with quality, while taking care that the generations that come after us also have this opportunity.

Keywords: *additive technologies, surface roughness, costs, economic aspect, sustainable development .*

1. Introduction

Additive manufacturing or three-dimensional (3D) printing is the controlled addition of materials, carried out by successively applying layers of materials until a predefined shape is formed. It enables the creation of objects of different complexity and size. 3D printing, transforms traditional manufacturing by building objects layer by layer from digital designs. It enables rapid prototyping, customization, and efficient production of complex geometries while minimizing material waste. (Šimunić, Kostadin, Stipaničić and Grgurić, 2024.)

Unlike traditional processes such as injection molding, milling or casting, which use a top - down principle, with additive technologies, the reverse principle is present: bottom - up. (Badiru, Valencia and Liu, 2017.)

Additive technology includes the following steps: CAD model creation, CAD model conversion to STL file, STL file transfer to AM machine, AM machine parameters adjustment, prototyping, prototype removal, post-processing (if needed) and use. (Gibson, Rosen and Stucker, 2015.)

Surface roughness is, in a general sense, a micro-geometric irregularity of the surface, which occurs during processing procedures or other influences. Surface roughness in certain cases significantly affects the working properties of machine parts, especially at the points of mutual connection of individual elements (friction, clearance, lubrication...). In general, machined parts with lower roughness have higher dynamic strength, higher corrosion resistance, higher fitability, better heat transfer, etc. As achieving a low degree of roughness is always connected with longer and more expensive machining processes, it results in an increase in the price of the machined part.

The main goal of this paper is to evaluate and investigate the primary factors of AM production in terms of quality and surface roughness based on test samples. In this work, the surface roughness parameters are measured: R_a, R_z i R_{max}. (Feketić, 2022.)

Also, the aspect of economic profitability of the application of the processed procedures is dealt with, and after the analysis of the obtained results, the main conclusions are drawn.

2. Theoretical elaboration

Today, additive manufacturing has developed a lot, and is widely used, and thus the materials used are gaining more and more importance.

As materials and their selected properties are subject to constant improvements and rapid changes, it is difficult to keep track of their classifications. It is important to note that the material only partially determines the result of the AM process, and the overall quality of the products is influenced by various parameters. Thus, in addition to choosing the optimal material, it is important to take care of the selected additive manufacturing process and construction solution.

With additive manufacturing, which is carried out in layers, there is a recognizable difference in properties. In this case, we speak of anisotropy, i.e. that the properties vary in different directions and values. Layer-oriented production, assisted by AM processes, actually generates anisotropic formations. The degree of anisotropy can vary; from barely recognizable to a degree that has a significant impact on stability. Although mainly dependent on the AM process, the orientation of the part being made and the design solution also play an important role. (Gebhardt, 2012.)

For special applications, AM compounds are usually post-processed to improve microstructure, reduce porosity and improve surface quality, reduce roughness and meet geometric tolerances.

Today, AM enables the processing of materials of all classes, i.e. polymers, metals and ceramics, and their combinations in the form of composites.

Special importance should always be given to the costs, i.e. the economic profitability of production, and for this reason, new materials and technologies are being researched.

The first group of materials used in additive manufacturing are polymer materials, which are still the most common today.

For selective laser sintering (SLS), the preferred materials are polyamides (PA). Although polyamides are often used for injection molding, they differ significantly from those used in AM processes. Primarily, even if the material were chemically identical, the final products would be very different. The material that is completely melted and injected into the mold under high pressure shows different properties compared to the same one that is locally melted under atmospheric pressure, and is deposited in layers and solidified by thermal conductivity. Industrial products are typically made of PA6, while SLS mainly uses PA11 or PA12.

Compared to other methods, FDM (fused deposition modeling) technology has its advantages, such as the variety of production and low material costs, which is why it is the most commonly used method. (Šančić and Tomašić, 2022.)

For FDM processes, the base material is acrylonitrile/butadiene/styrene (ABS). Because ABS is often used as an injection molding material, it is considered a standard engineering material.

As the development and production of new products requires high-quality polymer materials, materials such as polyphenylsulfone (PPSF / PPSU) and polyetheretherketone (PEEK) appeared on the market. PEEK has excellent chemical properties, is resistant to flame and high temperature, is light and has high tensile strength. Also, the materials come in different colors, but it is easier to use with AM processes that have the supply of materials from a special container (eg FDM process). The reason for this is the need to replace the entire material stored in the machine and to make the product from the treated color in processes that store the material inside the manufacturing chamber (e.g. SLS process). (Gebhardt, 2012.)

In conclusion, it can be said that the variety of polymer materials that can be used in additive manufacturing is increasing.

The examined parameters of roughness [in μm] in this paper are: R_a (arithmetical mean deviation of the profile), R_z (mean height of roughness) and R_{max} (highest height of roughness).

Surface roughness is the result of surface irregularities inherent in the machining process, not the machine, but which does not include waviness, deviation from form, and surface defects. Roughness includes short-wave surface irregularities. It is generally a consequence of the production process.

It is quantified by vertical deviations of the actual surface from its ideal shape. If these deviations are large - the surface is rough, and if they are small - the surface is smooth.

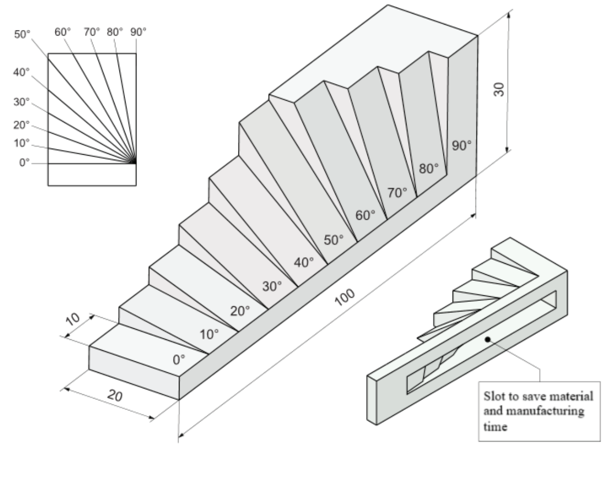
3. Materials and methods

The materials, methods, equipment and used test procedures are listed below.

Test sample is created using software CATIA V5-6R2019 (Dassault Systèmes), and the final 3D model is exported in the form of an STL file, which enables import into a program for cutting layers, connected to an AM machine.

The sample consists of a square block with dimensions of 100x20x30 [mm], which is divided into ten equal surfaces inclined from 0° to 90° to the horizontal plane, in steps of 10°, as shown on Figure 1. (Feketić, 2022.)

Figure 1 Test sample



In this way, ten simple design surface configurations were achieved on the sample, which can be examined from the top side. The lining on the bottom serves as a support and prevents deformation during the time of use, which is limited by the characteristics of the material.
A slot is placed on the back side in order to save material and manufacturing time, and it also does not require the use of a support structure and its subsequent removal. It is dimensionally large enough to provide good access for roughness testing by contact methods, and allows repeatability of measurements.
An auxiliary device and a device for measuring the surface roughness were used from the equipment, and after the measurement the results were statistically processed and analyzed.
The materials used are: PLA - polylactic acid - a biopolymer produced from renewable and natural raw materials such as corn starch and sugar cane, then PETG (polyethylene terephthalate glycol) - which has good physical properties and durability, and PA12 (polyamide) - better known as nylon, which is an engineering plastomer for functional prototyping and end-use manufacturing.
Figure 2 shows the test samples with characteristics for carrying out the measurements, Figure 3 shows roughness measurement procedure, while Table 1 lists the characteristics of the test samples. (Feketić, 2022.)

Figure 2 Test samples with characteristics for carrying out measurements

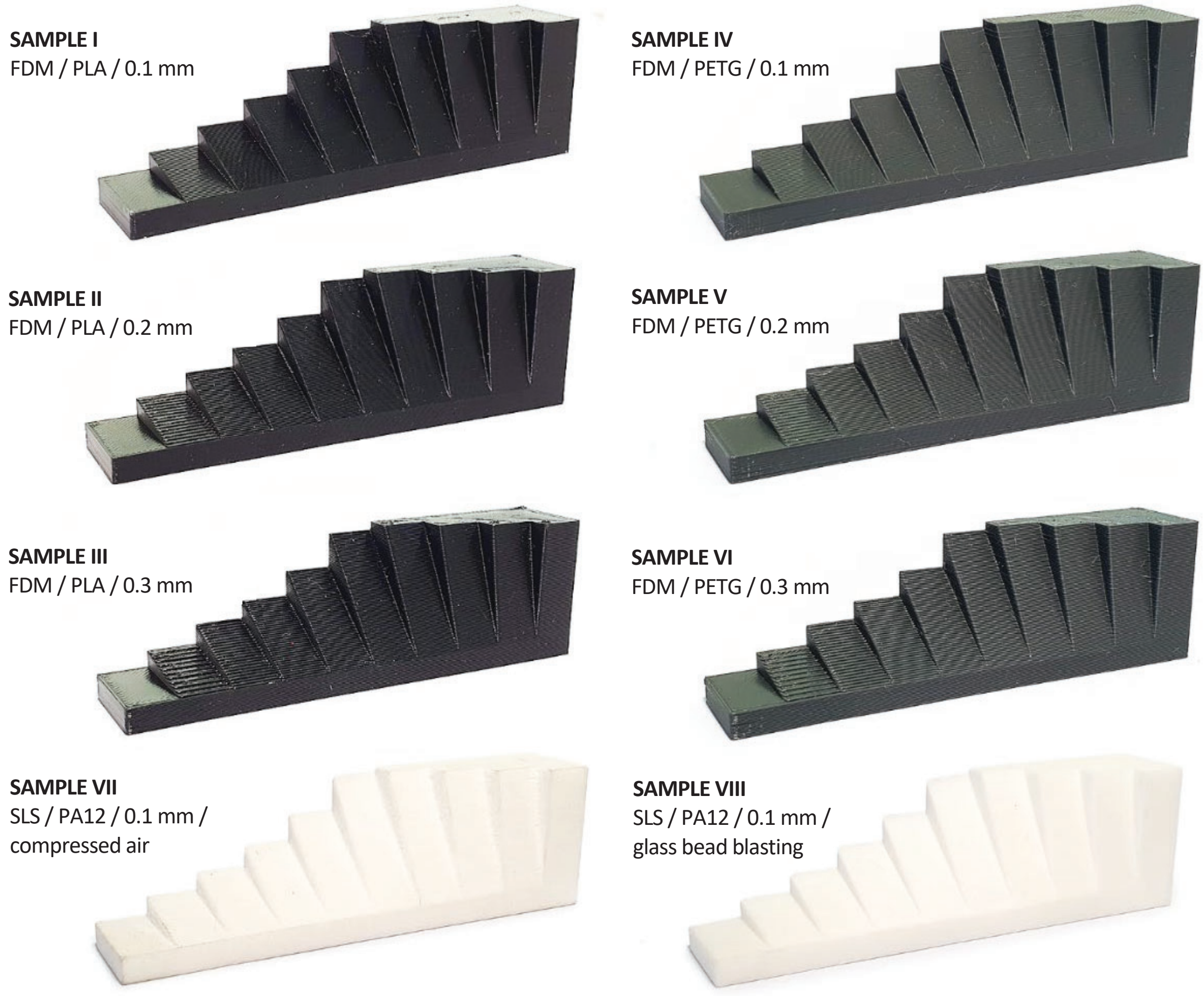


Figure 3 Roughness measurement procedure

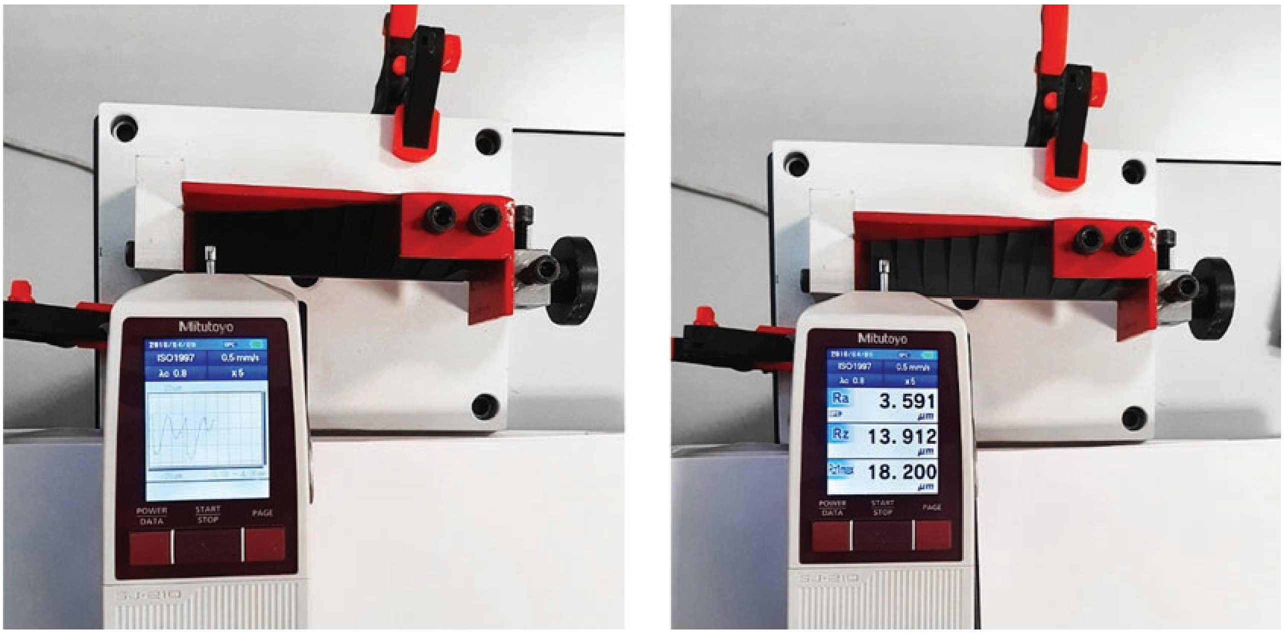


Table 1 Characteristics of the test samples

Sample	Technology/ process/ machine	Material	***Layer thickness*** *(mm)*	Subsequent treatments
I	Material extrusion / FDM / Prusa i3 MK2	PLA	0.1	Not used
II			0.2	
III			0.3	
IV		PETG	0.1	
V			0.2	
VI			0.3	
VII	PBF / SLS / Eos Formiga P110	PA12	0.1	Compressed air
VIII				Glass bead blasting

4. Results and analysis

Here are the test results for all three tested materials (PLA, PETG i PA12). (Feketić, 2022.)

Table 2 Measurement results of samples made by FDM process for PLA material

Surface incline	Surface roughness parameters (μm) / Standard deviation								
	SPECIMEN I *Layer tickness: 0.1 mm* *Material: PLA*			**SPECIMEN II** *Layer tickness: 0.2 mm* *Material: PLA*			**SPECIMEN III** *Layer tickness: 0.3 mm* *Material: PLA*		
	$\overline{Ra}$	$\overline{Rz}$	$\overline{Rmax}$	$\overline{Ra}$	$\overline{Rz}$	$\overline{Rmax}$	$\overline{Ra}$	$\overline{Rz}$	$\overline{Rmax}$
	σ_{Ra}	σ_{Rz}	σ_{Rmax}	σ_{Ra}	σ_{Rz}	σ_{Rmax}	σ_{Ra}	σ_{Rz}	σ_{Rmax}
0°	4,138	17,796	22,254	5,913	25,920	29,498	5,573	25,073	28,179
	0,131	0,399	0,879	0,078	1,646	2,550	0,125	0,468	0,589
10°	15,382	79,819	83,394	14,421	83,216	112,400	14,007	82,192	142,910
	0,965	3,034	4,645	0,293	5,011	0,521	0,705	1,141	6,475
20°	20,978	79,385	82,362	25,384	113,857	122,507	21,783	116,467	128,720
	0,319	0,981	2,445	1,512	3,806	4,833	1,252	5,013	1,908
30°	18,151	73,683	79,962	30,769	116,300	121,880	31,423	130,947	139,570
	0,795	2,237	3,195	1,321	2,283	5,573	2,225	4,866	15,411
40°	13,866	64,254	72,286	26,039	106,163	110,250	29,363	127,570	144,653
	0,302	0,471	4,744	0,681	2,504	3,349	1,210	5,032	22,878
50°	11,821	62,536	67,320	20,016	88,950	95,063	25,842	116,417	131,080
	0,235	1,006	2,730	0,471	0,635	2,469	0,526	2,501	13,479
60°	9,511	49,078	56,005	17,265	77,309	80,952	23,546	102,980	110,027
	0,214	1,287	1,196	0,234	2,564	4,088	0,424	2,176	6,387
70°	8,605	43,856	51,840	14,457	66,167	72,206	21,490	95,244	103,289
	0,342	1,644	4,317	0,371	2,822	5,806	0,405	2,482	5,949
80°	8,596	42,933	52,609	13,817	63,119	68,340	19,758	88,532	94,025
	0,295	0,870	7,730	0,162	0,648	2,007	0,216	1,260	2,163
90°	7,565	39,155	44,054	13,562	62,206	65,151	19,301	85,415	91,008
	0,162	1,724	3,897	0,208	1,829	2,296	0,624	0,844	2,969

Table 3 Measurement results of samples made by FDM process for PETG material

Surface incline	Surface roughness parameters (μm) / Standard deviation								
	SPECIMEN IV *Layer tickness: 0.1 mm* *Material: PETG*			**SPECIMEN V** *Layer tickness: 0.2 mm* *Material: PETG*			**SPECIMEN VI** *Layer tickness: 0.3 mm* *Material: PETG*		
	$\overline{Ra}$	$\overline{Rz}$	$\overline{Rmax}$	$\overline{Ra}$	$\overline{Rz}$	$\overline{Rmax}$	$\overline{Ra}$	$\overline{Rz}$	$\overline{Rmax}$
	σ_{Ra}	σ_{Rz}	σ_{Rmax}	σ_{Ra}	σ_{Rz}	σ_{Rmax}	σ_{Ra}	σ_{Rz}	σ_{Rmax}
0°	3,577	15,306	20,157	5,622	24,999	29,737	4,560	22,877	27,086
	0,297	0,189	0,418	0,112	1,306	4,882	0,183	0,929	0,725
10°	13,610	72,041	83,020	14,548	87,346	121,977	15,850	88,768	145,510
	0,764	6,544	0,652	0,206	0,107	4,308	1,167	7,729	1,781
20°	21,641	81,345	85,434	26,253	121,110	126,127	23,659	133,907	150,257
	0,157	0,610	3,925	0,417	2,098	2,960	0,135	12,294	4,457
30°	18,569	73,462	77,423	30,445	116,857	120,103	26,071	126,023	128,190
	0,201	1,498	1,606	0,431	0,637	0,067	0,738	2,620	3,044
40°	14,779	69,360	76,742	28,161	109,513	116,130	29,804	125,207	128,880
	0,150	2,439	1,655	0,248	3,782	3,068	0,180	0,701	2,121
50°	11,496	59,903	70,124	23,744	98,318	106,193	27,862	118,010	121,583
	0,230	3,322	10,336	0,322	2,202	4,774	0,920	1,747	1,789
60°	9,926	53,390	60,739	18,576	84,806	90,549	25,944	110,023	116,097
	0,604	2,060	7,154	0,101	0,197	4,027	0,224	1,357	3,577
70°	8,357	41,740	46,733	16,913	77,036	81,029	22,955	100,520	103,983
	0,455	3,115	6,915	0,308	1,442	1,849	0,142	0,519	2,237
80°	8,208	40,802	47,479	14,954	66,937	70,801	21,231	94,095	98,529
	0,581	2,502	7,909	0,301	1,162	3,089	0,294	1,779	1,828
90°	7,839	39,154	44,674	14,030	64,071	66,900	20,647	91,938	96,014
	0,440	2,236	0,282	0,064	1,473	2,439	0,150	0,753	1,758

Table 4 Measurement results of samples made by SLS process for PA12 material

Surface incline	Surface roughness parameters (µm) / Standard deviation					
	SAMPLE VII *Layer tickness: 0.1 mm* *Material: PA12* *Subsequent treatment: Compressed air*			**SAMPLE VIII** *Layer tickness: 0.1 mm* *Material: PA12* *Subsequent treatment: Glass bead blasting*		
	$\overline{Ra}$	$\overline{Rz}$	$\overline{Rmax}$	$\overline{Ra}$	$\overline{Rz}$	$\overline{Rmax}$
	σ_{Ra}	σ_{Rz}	σ_{Rmax}	σ_{Ra}	σ_{Rz}	σ_{Rmax}
0°	11,923	62,793	75,747	6,979	33,830	44,334
	0,191	5,368	7,197	0,192	2,402	5,954
10°	16,643	87,230	106,670	15,874	72,896	94,029
	0,471	2,238	6,601	1,124	6,061	2,252
20°	14,451	79,353	90,776	16,367	73,269	90,220
	0,587	1,218	3,112	0,184	1,400	5,340
30°	13,874	75,144	89,814	13,904	59,927	78,846
	0,665	5,100	7,539	1,487	3,855	0,599
40°	12,854	67,782	87,609	11,846	52,503	66,163
	0,655	4,787	14,674	0,872	2,931	5,834
50°	12,432	69,802	83,594	9,290	45,860	64,911
	1,216	7,307	5,627	0,139	2,444	6,696
60°	12,372	70,346	82,140	8,788	42,756	53,433
	1,551	11,804	14,152	0,255	2,915	2,044
70°	12,841	70,551	88,172	8,445	39,342	50,853
	0,888	4,309	12,018	0,453	2,490	2,753
80°	12,891	71,141	87,774	7,853	40,093	57,378
	1,055	4,176	3,821	0,756	4,531	16,175
90°	11,511	65,375	79,023	6,844	35,655	48,780
	0,835	2,459	0,282	0,074	3,394	6,836

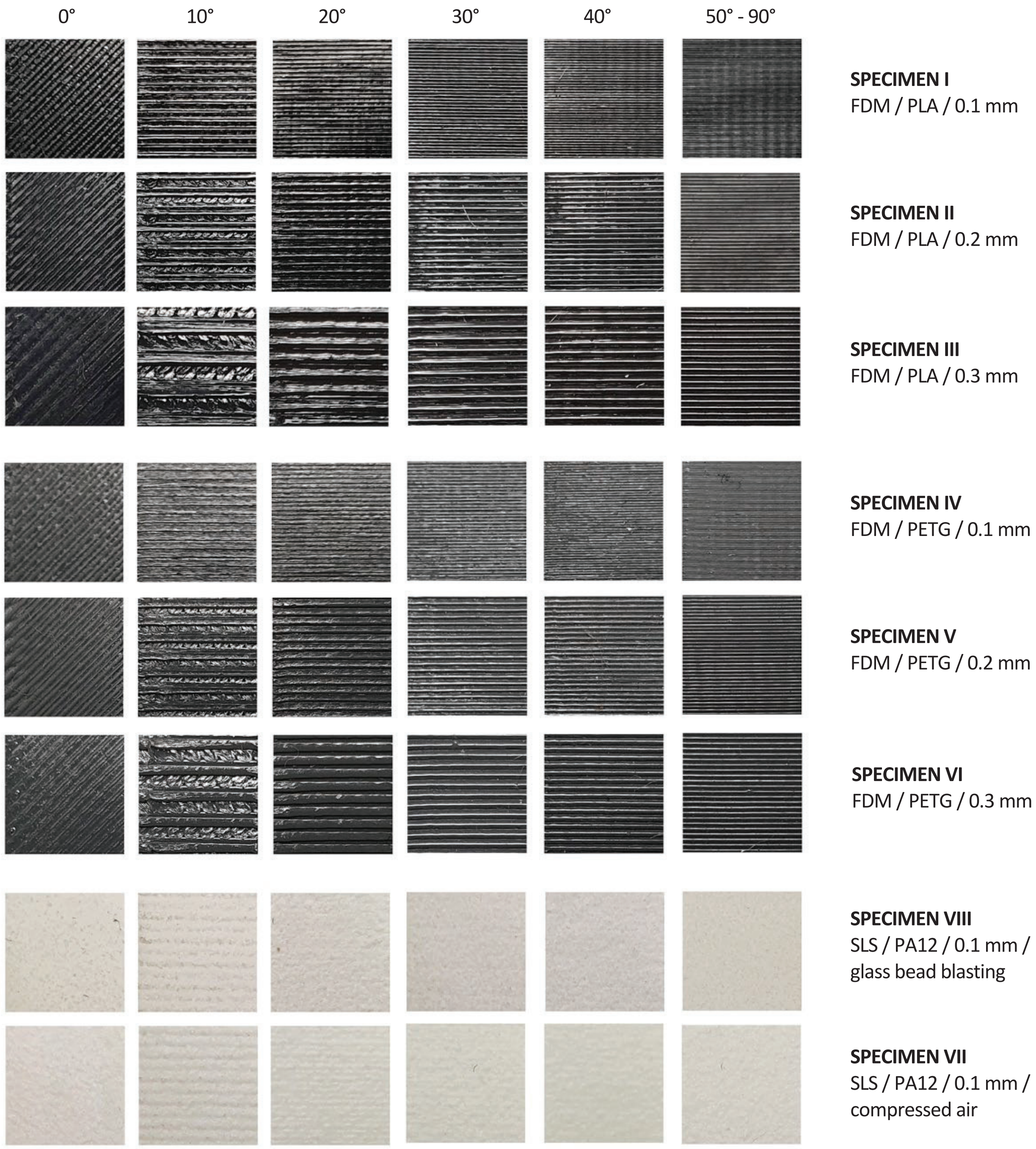
By analyzing and comparing the results based on the used AM technologies, it is evident that the SLS process has a much smaller dependence on the surface inclination, as far as the influence on the roughness is concerned, compared to FDM.
Thus, the range between the maximum and minimum values of the R_a parameter, for all slopes of inclination and layer thickness, in the SLS process is between 5,132 – 9,523 µm, while in the FDM process it is 16,840 – 25,850 µm. The same applies to the parameters R_z and $R_{max.}$
This means that with the SLS process, roughness variations can be reduced, i.e. it is possible to achieve somewhat approximate results regardless of the slope of inclination, unlike the FDM process, where the dispersion is relatively greater.
As expected, the best minimum roughness values were achieved at slopes of inclination of 0° or 90°. With the FDM process, the results show the best values at 0°, followed by those obtained at 90° or 10°. Their range is quite large, so for the R_a parameter it is 3,427 – 11,290 µm.
Comparatively, the SLS process achieves the best values at 90°, then at 0°, where the range is very small and amounts to 0,136 – 0,412 µm. The similarity was also observed for the parameters R_z and $R_{max.}$
The analysis of these data shows the influence of the chosen orientation of the product, which is more pronounced in the application of the FDM process. (Feketić, 2022.)

Table 5 shows the maximum and minimum values of the surface roughness parameters, while Figure 4 shows surfaces of specimens during the visual inspection . (Feketić, 2022.)

Table 5 Maximum and minimum values of the surface roughness parameters

Specimen	Surface roughness parameters (µm)								
	R_a			R_z			R_{max}		
	Surface incline		Difference	Surface incline		Difference	Surface incline		Difference
	MIN	MAX		MIN	MAX		MIN	MAX	
I	0°	20°	16,840	0°	10°	62,023	0°	10°	61,140
	4,138	20,978		17,796	79,819		22,254	83,394	
II	0°	30°	24,856	0°	30°	90,380	0°	20°	93,009
	5,913	30,769		25,920	116,300		29,498	122,507	
III	0°	30°	25,850	0°	30°	105,874	0°	40°	116,474
	5,573	31,423		25,073	130,947		28,179	144,653	
IV	0°	20°	18,063	0°	20°	66,039	0°	20°	65,277
	3,577	21,641		15,306	81,345		20,157	85,434	
V	0°	30°	24,823	0°	20°	96,111	0°	20°	96,390
	5,622	30,445		24,999	121,110		29,737	126,127	
VI	0°	40°	25,244	0°	20°	111,029	0°	20°	123,170
	4,560	29,804		22,877	133,907		27,086	150,257	
VII	90°	10°	5,132	0°	10°	24,437	0°	10°	30,923
	11,511	16,643		62,793	87,230		75,747	106,670	
VIII	90°	20°	9,523	0°	20°	39,439	0°	10°	49,696
	6,844	16,367		33,830	73,269		44,334	94,029	

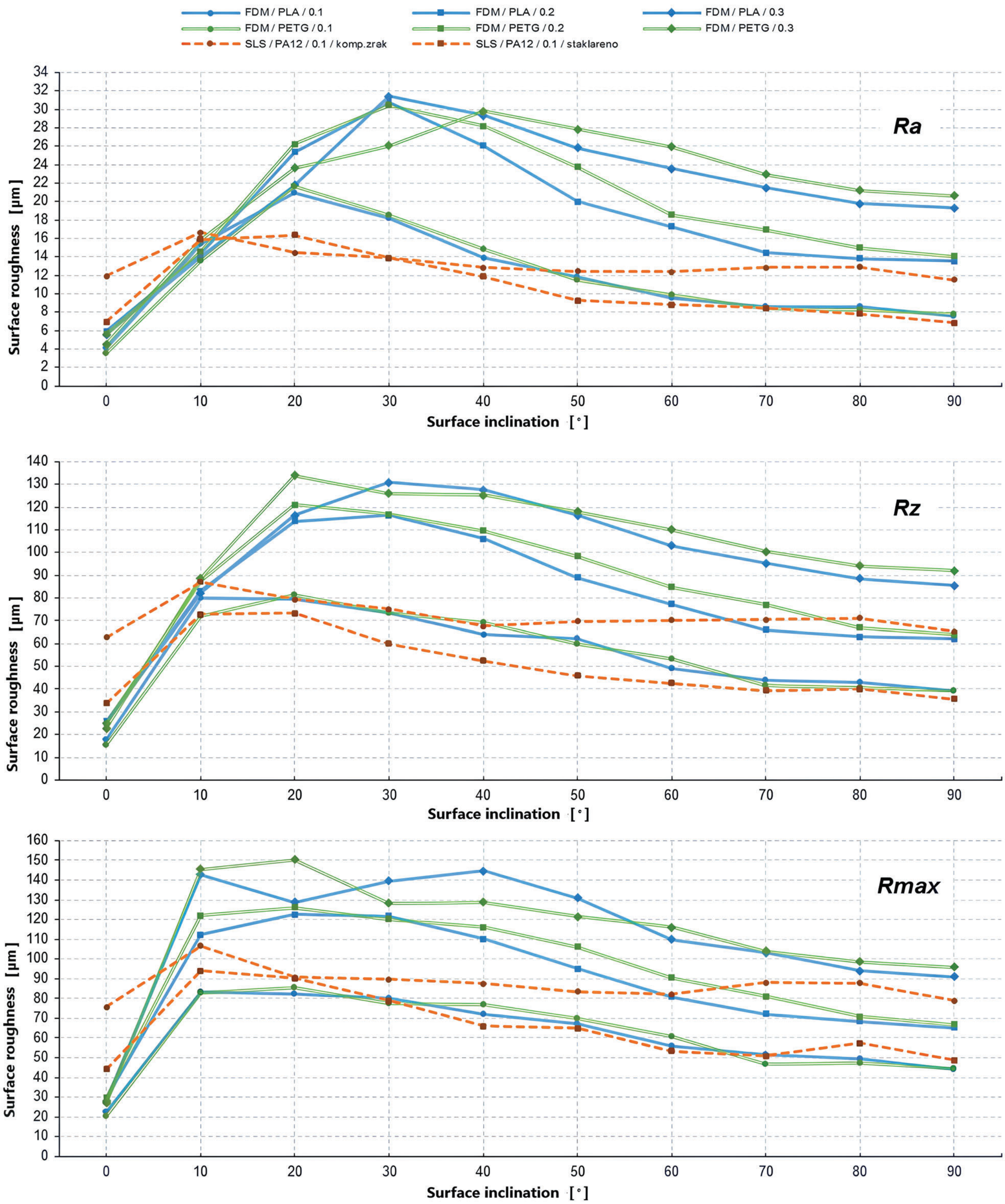
Figure 4 Surfaces of specimens during the visual inspection



Also from an economic point of view, it should be said that it is important to investigate the possibilities of individual materials and additive technologies to achieve the lowest possible values of surface roughness parameters, because this reduces the costs of possible subsequent processing, which favorably affects both the quality and the final price of the product.

Finally, Figure 5 graphically shows the comparison of the results according to the roughness parameters R_a, R_z and R_{max}.

Figure 5 Comparison of the results according to the roughness parameters



5. CONCLUSION

Additive technologies are used to produce products with a certain surface quality, which results from the characteristics of the process, given that it is about stacking materials layer by layer, i.e. the bottom-up principle.

The geometric 3D model does not include surface defects, but they arise from the manufacturing process, depending on the technological parameters.

It is very important to examine and analyze the surface roughness when creating products using additive technologies, in order to obtain products of the highest quality, without the need for subsequent treatment, which will favorably affect the reduction of costs, that is, the economic profitability of the described processes.

In this paper, an examination of the surface roughness parameters (R_a, R_z and R_{max}) of test samples, which were made using FDM and SLS processes from three different materials: PLA, PETG and PA12, was carried out. Two types of subsequent treatment were used: compressed air and glass bead blasting. The influence of the slope of the surface and the thickness of the layer is observed.

The results were presented and statistical processing and analysis was done, after which the following conclusions and recommendations for further research were made.

There is a need for further improvement of surface quality for additive manufacturing.

Further experimental research needs to be carried out in response to industrial needs, along with standardization of roughness measurements and test samples for different AM technologies and processes.

Increasing the thickness of the layer results in a worse quality of the processed surface (worse surface roughness).

There is a clear mutual connection with the geometric feature of the slope of the surface, i.e. the increase in thickness shifts the slope angle where the critical value of roughness is achieved. As the slope increases (from 0° to 90°), the values reach their maximum from 10° to 40°, after which they decrease with a further increase in the slope from 50° to 90°.

As a criterion for improving surface quality in the FDM process, it is recommended to use reduced layer thickness values and avoid using surface slopes from 10° to 40° to reduce the stairs effect and reduce oscillations between the minimum and maximum roughness values. By using PETG material, better results are achieved compared to PLA material.

The SLS process produces products of better quality, reduced stairs effect and reduced roughness variations, compared to the FDM process, i.e. achieving somewhat approximate roughness results regardless of surface inclination. In order to improve the quality of the surface, the use of slopes from 10° to 40° should also be avoided with the use of subsequent treatment (compressed air, glass bead blasting and others). On average, 21% - 32% better results of the roughness parameter were achieved by glass bead blasting. (Feketić, 2022.)

In conclusion, additive manufacturing techniques offer enormous potential because they adapt well to the geometric complexity and design of the product being made.

The advantages are numerous, such as: lighter and more ergonomically acceptable products, products made of more materials, short production cycles, fewer assembly errors resulting in lower associated costs, lower investment costs in tools, combination of different production processes, optimal use of materials and sustainable production. Conventional production is mainly limited by the size and geometric complexity of the products, with the frequent use of processes and tools that increase the final price of the product.

On the other hand, the disadvantages of additive manufacturing are: the finish of complex surfaces can be extremely rough, long manufacturing times, materials with limited mechanical and thermal properties that limit performance under stress, and greater tolerances than with other manufacturing methods, such as methods based on material removal .

However, regardless of all the limitations, additive manufacturing can be applied in many sectors where it is easily adapted to the requirements of each of them. Designing and manufacturing using 3D printing is considered one of the biggest industrial revolutions of the last few years, and its use is predicted to increase in the future.

In conclusion, it is necessary to emphasize the economic aspects of the application of the described processes. First of all, the lower costs of tools should be highlighted. Also, by achieving a lower surface roughness, which is obtained with AM products, the need for subsequent treatment is reduced, which reduces the price of the product. As the materials used in the FDM process are also cheaper, this also contributes to economic profitability, so this can also be added to the previously described advantages of additive manufacturing.

This work contributes to the research of new, modern and innovative technologies and materials, and their properties.

PLA material for example is a biopolymer, while PA 12 is biocomatible material and these properties are very important in modern technologies.

By using new and innovative materials and technologies, we also influence on sustainable development, which speaks of the fact that we need to meet our needs with quality, while taking care that the generations that come after us also have this opportunity, that is, that we leave a quality place for living, for the generations behind us.

6. REFERENCES

1. Badiru, A. B., Valencia, V. V., Liu, D. (2017) Additive Manufacturing Handbook: Product Development for the Defense Industry, CRC Press - Taylor & Francis Group, Boca Raton.
2. Feketić, Z. (2022) Utjecaj debljine sloja i nagiba površine na hrapavost probnih uzoraka dobivenih aditivnim tehnologijama, Graduation thesis, Karlovac University of Applied Sciences, Karlovac.
3. Gebhardt, A. (2012) Understanding Additive Manufacturing, Carl Hanser Verlag, München.
4. Gibson, I., Rosen, D., Stucker, B. (2015) Additive Manufacturing Technologies - 3D Printing, Rapid Prototyping and Direct Digital Manufacturing, Springer-Verlag, New York.
5. Šančić, T., Tomašić A. (2022) Ispitivanje mehaničkih svojstava materijala proizvedenih taložnim sraščivanjem, 8th International Conference „Vallis Aurea" 2022, Požega.
6. Šimunić, N., Kostadin, T., Stipaničić, I., Grugrić, I. (2024) Safety measures in additive manufacturing, 9th International Professional and Scientific Conference „Occupational Safety and Health" 2024, Zadar,