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INVESTIGATION OF THE DEPTH IMPACT OF THE IRONING PROCESS USING SEM IMAGES AND CAD SYSTEM

PÉTER FICZERE[1] – NOÉMI LÁSZLÓ[1,2]

[1]Budapest University of Technology and Economics,
Department of Railway Vehicles and Vehicle System Analysis,
1111, Budapest, Műegyetem rkp. 3.
[2]H-ION Kutató, Fejlesztő és Innovációs Kft. – SEM Labor
[1]ficzere.peter@kjk.bme.hu, [2]noemi.laszlo@h-ion.hu
[1]https://orcid.org/0000-0003-3207-5501, [2]https://orcid.org/0000-0002-8912-2711

Abstract: The adoption of additive manufacturing within the automotive sector is progressively growing, primarily attributed to the technology's speed, relative ease of use, and its capability to manufacture components with intricate geometries that are beyond the reach of traditional methods. This holds especially true for enhanced or structured plastic parts. A variety of instrumental, analytical, and image analysis techniques are accessible for both qualitative and quantitative assessment of surface structures. This article outlines the potential of utilizing scanning electron microscopy (SEM) and CAD for image analysis in this context.

Keywords: *ironing, SEM, CAD, Additive manufacturing, surface topology, FDM*

1. INTRODUCTION

The implementation of Industry 4.0, which is now expected in an increasing number of areas, poses many challenges. Industry 4.0 imposes a number of conditions, of which the need to use additive manufacturing technologies becomes clear if we only think of the specific requirements to be met and the need to react quickly. The role of additive manufacturing technologies has changed significantly in recent times, and they are no longer seen as a marketing tool or a rapid prototyping process. Quality requirements have changed accordingly. Not only the correct geometric design, but also criteria for dimensional accuracy, colour, shape, feel and material suitability, as well as appropriate load-bearing capacity, are being set. As a result, the additive manufacturing engineer today needs to have a much more profound knowledge than before. It is easy to see that, if we think only about the appropriate load-bearing capacity, the use of generative design, developed to exploit the specific features and advantages of additive manufacturing technologies and supported by artificial intelligence, is now essential (Albert & Takács, 2023), (Borsodi & Takács, 2022). The surfaces of parts created by additive manufacturing technologies do not guarantee the quality expected in the engineering field, and therefore often require some kind of surface improvement process. However, these processes not only modify the surface quality, but also the morphology of the material. It is therefore important to understand the effect of the parameters of each process on surface quality and morphological changes. Achieving uniform surface qualities as a goal is particularly difficult for parts produced by layer-by-layer build-up, where the manufacturing technology results in parts with different material properties and surface qualities in different directions.

The application of surface modification processes is becoming increasingly common for parts produced by additive manufacturing. Additive manufacturing or 3D printing uses innovative methods to produce parts layer by layer. These parts often have to meet different functional and aesthetic requirements, and surface modification processes are used to meet these requirements.

These processes can be chemical, mechanical, or coating and can be aimed at improving mechanical properties, smoothing the surface or modifying technical properties. For example, surface treatment may be used to apply coatings to the parts to increase wear resistance or corrosion resistance. In addition, laser surface treatment and the use of electrochemical processes are also becoming increasingly common in additive manufacturing. The best-known surface finishing processes are machining (Kónya & Ficzere, 2023), (Kónya & Ficzere, 2022), rolling, coating and ironing (Alzyod, Takács, & Ficzere, 2023).

In the present study, the effect of the parameters of the ironing process used in FFF (Fused Filament Fabrication) technology on the surface quality was investigated. The ironing process consists of "going through" the top layer again after a part has been printed, by holding the nozzle temperature but not or only very little material is deposited on the surface. This means that the high temperature (and very small amount of material) should cause the surface to merge more effectively, filling the gaps better and making the surface "smoother" and denser.

The investigated parameters are:

- ironing speed,
- rate of material addition,
- distance between the tool paths covered by the nozzle.

The test pieces were 10 mm edge length cubes from PLA material.

Previous studies (Ficzere, 2023) have shown that the surface roughness can be significantly reduced by the reinforcement process, as shown in Figure 1.

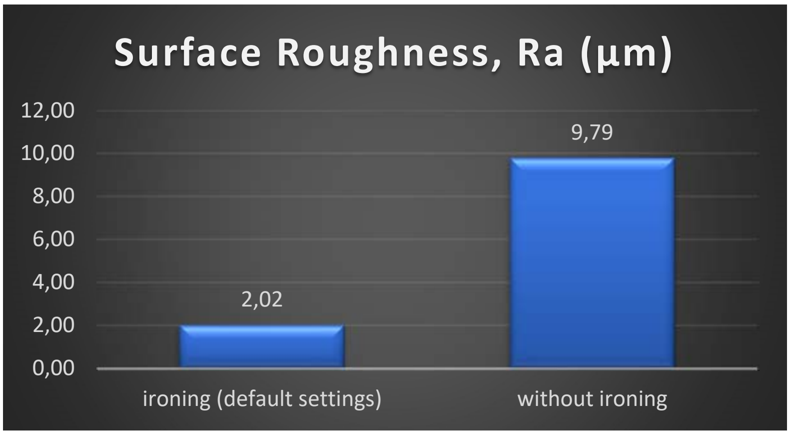

Figure 1. *Comparison of ironed and non-ironed surfaces (Ficzere, 2023)*

Since there is a clear correlation between surface roughness and dimensional accuracy (tolerances), it can be stated that parts with up to 4 tolerance classes more accurate (IT) can be achieved with ironed surfaces.

It was also established that the surface roughness increases with increasing ironing speed, but the increase is not significant. In addition, it can be stated that the smaller the deposited amount of material during the ironing process, the better the surface quality. However, it must also be seen that this is not significant. However, it is important to note that the smaller the ironing distance during the ironing process, the more efficient the process.

These tests were carried out with a Keyence VR-5000 microscope.

In addition to the results obtained, we wanted to investigate the depth changes of the reinforced layer during the ironing process. To do this, scanning electron microscope images were taken.

2. METHODOLOGY

In order to determine the dependence of the thickness of the ironed layer on the manufacturing parameters, test specimens were prepared with different settings. Table 1 shows the test parameters. The images for the test were taken with a Zeiss Sigma 300 scanning electron transmission electron microscope (FE-SEM).

Table 1

Test parameters to determine the thickness of the ironed layer

	Ironing speed (mm/s)	**Ironing distance (mm)**	**Flowrate (%)**	**Layer thickness (mm)**	**Ironed layer**
1	20	0.1	5	0.2	Top layer
2	80	0.1	5	0.2	Top layer
3	20	0.4	5	0.2	Top layer
4	20	0.1	20	0.2	Top layer
5	20	0.1	5	0.3	Top layer
6	20	0.1	5	0.4	Top layer
7	20	0.1	5	0.2	Every layer

Figure 2 shows a scanning electron microscope (SEM) image of an iron clad layer on one of the specimens.

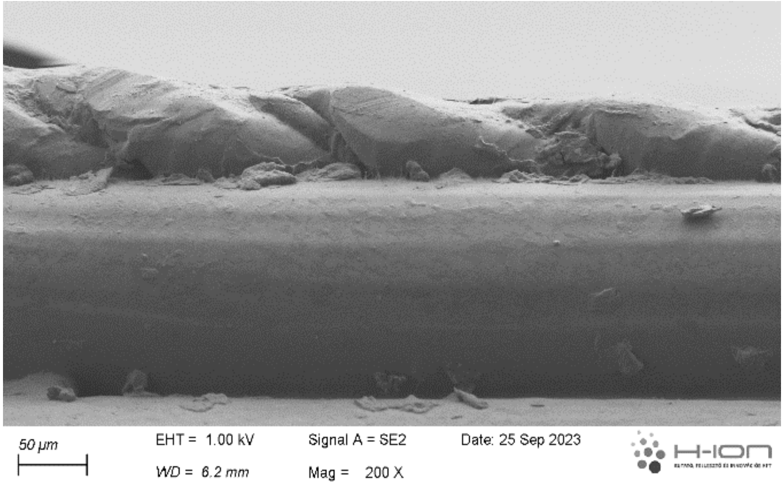

Figure 2. *SEM image of an ironed layer*

It can be clearly observed in the figure that the thickness of the resulting surface layer is not uniform. It is possible to measure at several locations, or even to examine the layer height in equal divisions over a base length, as we do for the average surface roughness, but it is clear that our average depends on where we measure. Of course, the more measurement locations, the more accurate the average layer thickness.

Today's CAD systems allow us to instantly generate all area information (area size, centre of gravity, moments, etc.) for areas bounded by closed curves. This allows us to insert SEM images taken for inspection purposes as backgrounds on a sketch plane. Next, based on the scale of the SEM images, we rescale the image to see it at true size. We then draw a contour around the layer of interest, as shown in Figure 3. It is important to note that this method can only be used if the sample itself has flat surfaces. A possibility of verification is to measure the known layer thickness under the ironed surface.

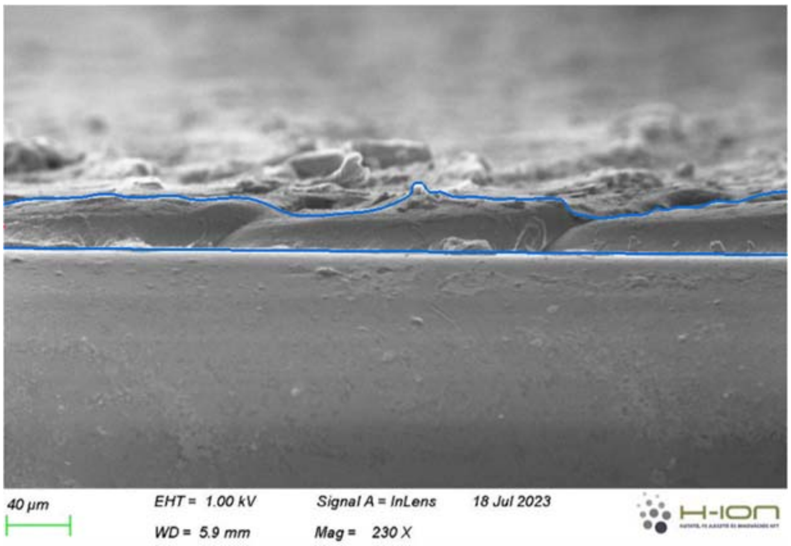

Figure 3. *Ironed layer drawn around in CAD system*

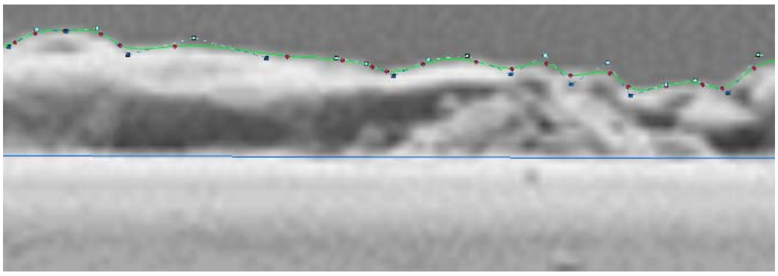

Figure 4. *NURBS curve approximated boundary of the ironed surface*

It can also be observed in Figure 4 that the base can be approximated practically well by a straight line, while the upper contour can only be approximated by a NURBS (Non-Uniform Rational Bezier Spline) curve of at least third order.
At the beginning and at the end of the inspected length, the section to be examined is closed by straight lines perpendicular to the base. In this way, we obtain the length and the size of the investigated area, as shown in Figure 5.
From this information, we can easily calculate that if we had a perfect surface - a rectangle would be the enclosed area - the height of this rectangle would be. This height is equal to the average height of the ironed layer.

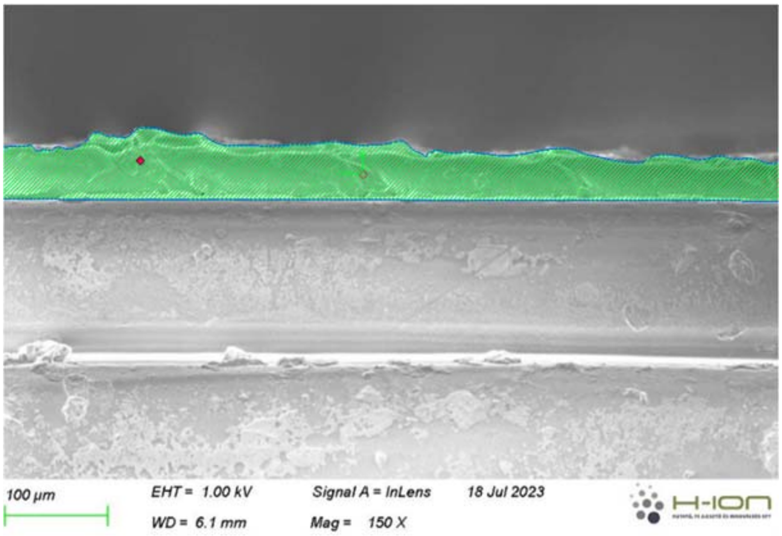

Figure 5. *Obtaining area information bordered by curves using CAD software*

The procedure presented here was used to examine the pieces for each parameter setting and calculate the average thickness of the ironed layers.

3. RESULTS

The average depth of the ironed layer measured under different production and ironing parameters is shown in Table 2. The base length, area and resulting depth of the ironed layer for the settings according to the series numbers in Table 1 can be read from Table 2.

Table 2

Results from CAD software based on SEM images

	Base length (µm)	Area covered (µm2)	Depth of the ironing (µm)
1	764.25	34420.95	45.04
2	228.2	2700.91	11.84
3	229.3	485.2	2.12
4	505.05	15687.26	31.06
5	229.42	7650.36	33.35
6	1618.56	193374.9	119.47
7	763.5	47460.71	62.16

4. ANALYSIS

The principal results of the study are summarised in Table 3.

Table 3

Ironing depth as a function of ironing parameters

	Ironing speed (mm/s)	Ironing distance (mm)	Flowrate (%)	Layer thickness (mm)	Ironed layer	Depth of the ironing (µm)
1	20	0.1	5	0.2	Top layer	45.04
2	80	0.1	5	0.2	Top layer	11.84
3	20	0.4	5	0.2	Top layer	2.12
4	20	0.1	20	0.2	Top layer	31.06
5	20	0.1	5	0.3	Top layer	33.35
6	20	0.1	5	0.4	Top layer	119.47
7	20	0.1	5	0.2	Every layer	62.16

Analysis of the results shows that:

- as the ironing speed increases, the depth of the ironed layer decreases,
- as the ironing distance increases, the depth of the ironed layer decreases,
- as the flow rate increases, the depth of the ironed layer decreases,
- the depth of the ironed layer increases in the case of for each layer ironed.

A discrepancy was found in the determination of the depth of the ironed layer as a function of the print layer thickness, so this requires further, repeated investigations. Figure 6 also clearly shows the ironed layer between the deposited layers.

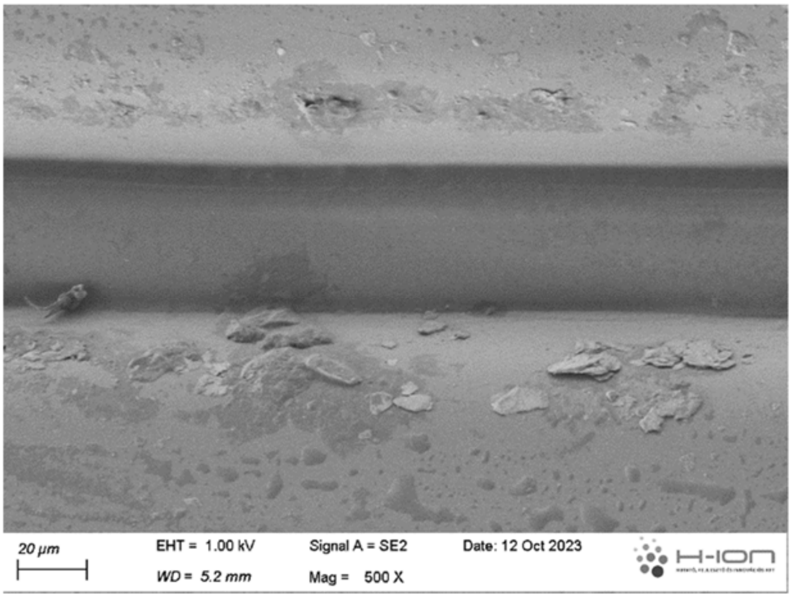

Figure 6. *SEM image of the ironed layer between printed layers*

5. SUMMARY

Taking into account the results of the examinations, it can be concluded that the ironing parameters have a significant effect on the depth of the ironed layer.

It is important to note that only one in-line test was performed in the present study, therefore, for more accurate and reliable results, it may be worthwhile to examine values taken in several cross-sections.

In order to increase the reliability of the results, CT (Computer Tomography) scans will also be performed in the future.

The results - the depth of the ironed layers - are also expected to have a significant effect on the mechanical properties, and we will continue our research in this approach.

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