PRINT SPEED AND ITS IMPORTANCE FOR METAL ADDITIVE MANUFACTURING

MARTIN NOZAR [1], JAKUB ROSENTHAL [2]

[1] Regional Technological Institute, Faculty of Mechanical Engineering, University of West Bohemia, Plzeň, Czech Republic

[2] Faculty of Mechanical and Environmental Engineering, OTH Amberg-Weiden, Amber, Germany

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nozar@rti.zcu.cz

The article deals with issues which occur when using different types of basic print speeds in metal additive manufacturing. It describes their importance, mutual relationships and their influence on the quality of pieces manufactured using this technology. The ability to manage the speed of the additive manufacturing process allows us not only to effectively improve print quality but also, for example, to reduce the volume of necessary support structures. It thus speeds up the whole printing process, minimizes material waste, and reduces the need for any finishing operations which may be necessary for achieving the required final properties of the printed parts. In this context, the connection between the quality and the speed of additive manufacturing is demonstrated in a simple experiment using Powder Bed Fusion technology (PBF) in which the effect of the print speed on various low-angled flat surfaces is observed.

KEYWORDS

Additive Manufacturing, PBF, Low-Angle Surface, Print Speed, Time-homogenization

1 INTRODUCTION

Many industrial companies are already successfully using additive manufacturing (AM) for producing objects from (not only) metallic materials and for replacing or supplementing conventional manufacturing methods. However, even though there are a lot of different AM machines on the market, the investment costs for the machines and for other necessary auxiliary equipment are still high. Therefore, in order for this investment to pay off, the manufacturers of these machines are constantly striving to improve their parameters, especially by increasing their print speed and enlarging the available building space.

An increase in the print speed is usually achieved by combining multiple laser beams, by using technology capable of printing multiple layers simultaneously, or by using advanced technologies that facilitate and speed up print preparation and subsequent post-processing. In addition to these technical improvements, there are a lot of technology options being developed related to setting up custom printing processes, which would make the whole process more effective, especially in terms of time and cost savings and improving the quality of the products. By using suitable settings of the printing process, it is possible to achieve better mechanical properties and better surface quality of printed pieces without the need for extensive post-processing [Hrbackova 2019]. This can be achieved by minimizing the internal stresses caused by the transfer of the thermal energy of the laser beam and subsequent temperature gradients from the surface to the centre of the AM part during cooling. In most cases, these stresses need to be removed by heat treatment [Diegel 2018].

Another advantage of using appropriate process parameters is a reduction in the volume of the support structures, which speeds up the printing process, and minimizes material waste (to some extent, it is also possible to save material by reducing the volume of the part itself and its support structure by using topological optimization or support-free design [Li 2017]) and reduces the need for post-processing. As proven experimentally, the lower surfaces could be reliably printed without supporting structures at angles less than the recommended 40° to 45°. There are several ways to do this: by using finer powder (i.e. particles of the same material but with a smaller mean size) or a special scanning strategy [Cloots 2017], setting experimental downskin parameters, or by controlled changes to the printing speeds, as demonstrated in the experiment described in this article.

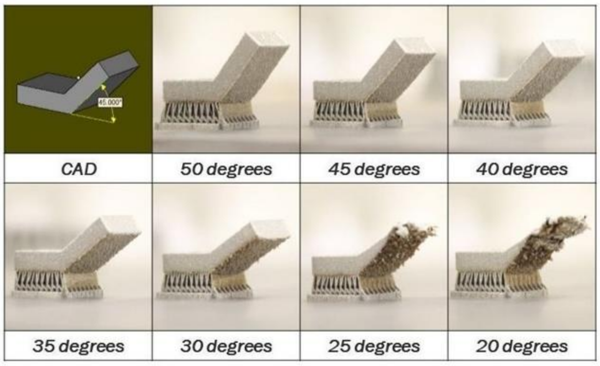

Figure 1. Generally expected quality of low-angle surfaces [Iliaifar 2020]

2 BASIC SPEEDS IN METAL ADDITIVE MANUFACTURING

Besides changes to the print speed for improving the quality of the printed parts, there is another important aspect to be considered – its effect on production or part delivery time. In metal AM, as well as in other manufacturing methods, the production speed is a key parameter along with manufacturing costs and the quality of manufactured pieces. High manufacturing speed means higher productivity and a faster return on investment, which is a significant competitive advantage. Although these two aspects would appear to contradict each other, it is not so clear-cut, and a reasonable solution to this problem can always be found [Nozar 2018].

There is obviously not just one type of print speed. It is possible to distinguish up to five different speeds in the additive manufacturing process. They depend on each other but differ in nature and their manifestations. In order to achieve the optimal overall manufacturing speed, it is advisable to optimize all its components, which does not always necessarily mean speeding them all up. During the printing process, for example, slowing down some parts of the printing process can cause better dissipation of the laser beam heat, which means a printed piece will not require such a large volume of support structures or finishing operations, which can lead to time savings and thus a shorter overall manufacturing time than would be achieved at the original speed. In order to be able to optimize the manufacturing speed and to evaluate the possibilities of improving the quality of the manufactured objects, it is necessary to distinguish these individual speeds to assess their significance and the possible impact on the entire manufacturing process and the quality of printed pieces.

2.1 Manufacturing (Production) Speed [number of specific pieces produced per unit of time]

The speed at which it is possible using a certain technology to produce particular objects with the required properties. It is determined by the total manufacturing time, which includes the time of all necessary activities from manufacturing preparation to finishing operations. Many relevant research studies [Gibson 2015], [Nozar 2018] in accordance with observations from practice confirm that the manufacturing time per part is the key factor to optimizing the costs of additive manufacturing.

The time spend on a whole building process consists of:

- Pre-Processing time (build model preparation, machine set-up, machine atmosphere generation, machine warm-up etc.)
- Processing time (scanning time, Z-axis movement, levelling, non-manufacturing movement of the nozzle/laser/head etc.)
- Post-processing time (cooling down time, machine cleaning, unused powder sifting, sawing pieces off from the platform, and any final finishing operations such as heat treatment, milling, polishing etc.)

The Manufacturing Speed is therefore directly dependent on the available equipment at all stages of the manufacturing process and on the capabilities of the operating personnel as well as on the quantity, dimensions, requirements and other specifics of the printed pieces, such as complexity of preparation, the necessary volume of support structures and the needed finishing operations (heat treatment, grinding, polishing, etc.). In the case of repeated manufacture (prints) or simultaneous manufacturing of several pieces, the production rate can be increased due to the time savings in the preparation or post-processing (e.g. shared heat treatment) operations. This speed, which is crucial for the customer, can therefore generally be improved at the organizational level, primarily through the efficient organization of the manufacturing process and ensuring that suitable manufacturing technologies are available. This speed has an indirect impact on the quality of the manufactured parts.

2.2 Volumetric Print Speed [printed volume per unit of time]

This speed is the printer's ability to create the required volume per unit of time and is thus one of its key parameters. It is primarily dependent on the printer performance (e.g. the number and power of the installed lasers) and on the specific setting of the process parameters. Thus, Volumetric Print Speed directly affects manufacturing speed. However, its key aspect, manufacturing time, also depends on the design of a particular print job. A certain volume can be printed in different orientations, which can mean, on the one hand, a different number of printing layers and, on the other hand, a different volume of required support structures, which can also have a different structure and thus a different Volumetric Printing Speed. This means that the experience of the operator also plays an important role in determining the Volumetric Print Speed, in addition to the technological sophistication of the printer. To ensure reliable and trouble-free printing, speeding up the printing process (e.g. by the suitable orientation of printed pieces and a minimum volume of support structures) and improving the quality of printed pieces (e.g. by reducing possible thermal deformations and internal stresses) it is now also possible to use thermal and mechanical software simulations of the printing process. The factors which this speed depends on directly affect the quality of the manufactured parts.

2.3 Layer Print Speed (Z-Speed) [number of printed layers (Z-axis distance) per unit of time]

The speed indicating the number of layers (in the entire volume or in a certain range) of a constant thickness printed per unit time. This speed changes during printing, mainly depending on the mass distribution of the printed object or objects in discrete layers as well as It also depends on the method used for creating the layers, the time taken for the layers to be printed and the Area Print Speed (described below).
This speed has a great influence on the quality of the printed pieces, since the duration of a single printing cycle affects the time available for dissipation of the laser beam's thermal energy from the fused powder, through the already printed parts or support structures to the printing platform. Insufficient removal of this energy can lead to overheating and internal stress in the printed pieces, which can cause a number of negative effects, such as poorer mechanical properties or cracks directly after removing the printed parts from the printing platform, or it can cause deformation and tearing of printed parts from the supporting structures during the printing process, which may interrupt the printing process due to the deformed parts colliding with the recoater.
This speed is directly dependant on Area Print Speed and recoater movement speeds and can be influenced by process parameters, above all by minimum layer time or by so-called 'ghost part'. A ghost part is a virtual object with the same process parameters as the real part, but the laser power is set to a very small non-zero value. Such an object, which can be a rotated duplicate of a printed piece, can be placed as needed at a suitable location on the printing platform in order to flatten the mass distribution curve of the individual layers (the curve belonging to the following experimental print job is shown in Fig. 1) and prolong the Print Time of certain layers thus reducing their Layer Print Speeds and provide a certain time homogenization.

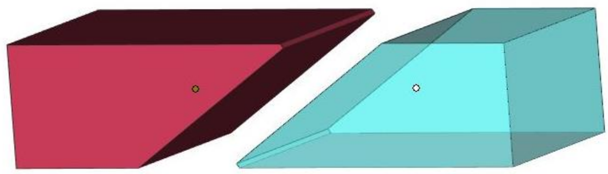

Figure 2. Printed object (left) and its virtual duplicate a 'ghost part'

2.4 Area Print Speed [printed area per unit of time]

The speed representing the print speed of the areas in a particular layer, i.e. the sum of areas belonging to the individual pieces which are sintered per unit time. This speed depends, on the one hand, on the total area printed in a given layer and on the mass distribution of this area including its complexity and, on the other hand, on the set process parameters, hence on the Scanning Speed. The effects of different settings used for printing downskin, upskin and inskin areas (which depend on the area content), are manifested at this speed, or at the time of printing a specific area in single layers.
This speed could be artificially influenced by software (e.g. available in EOS Print 2.x) [EOS 2021] functionality, above all by setting a minimum vector time (minimum time for each exposure vector which ensures that the energy applied does not overheat the area to be exposed), skywriting (decelerates/accelerates the Scanning Speed out of hatch lines

to provide constant energy input and thus better material properties), or various scanning strategies (e.g. sintering with or without defined stripes or chessboard pattern with different dimensions). This speed may also depend on different lengths of contoured edges of the printed pieces or special functions of time homogenization methods.

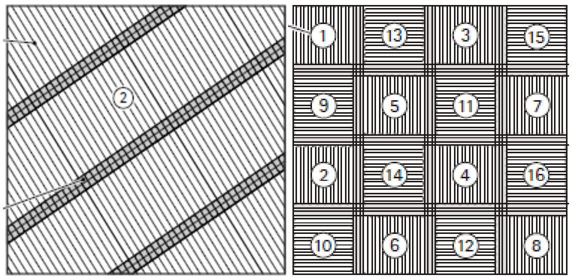

Figure 3. Examples of typical scanning strategies: stripes and chessboard [EOS 2021]

2.5 *Scanning Speed [laser path per unit of time]*

This speed is the basic process parameter and is the laser scanning speed along defined paths on the printed layer. Combined with the laser power it is a key process parameter influencing the ability of the laser beam to melt (or sinter) powder (especially in printing technologies such as Powder Bed Fusion). Its correct setting fuses the powder bed with the required properties and consequently creates compact layers with the desired properties and shape. This speed varies depending on the type of surface (especially downskin, upskin and inskin), for which other special process parameters are defined.

Efficiently setting up the printing process means finding the right combination of all the processing parameters, especially for the Scanning Speed and laser power, as these generate a stable melt pool of the optimum size [Saunders 2018]. Such combinations are found in the operating window shown in the P-V diagram in Fig. 4. This is where the laser energy is efficiently absorbed by the powder, creating a melt pool of sufficient depth to fuse strongly with the layer below it whilst avoiding excessive re-melting.

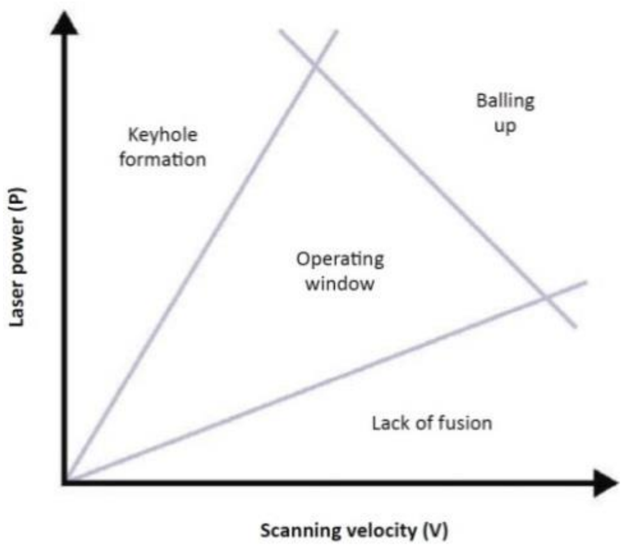

Figure 4. Operating window [Saunders 2018]

As is evident from the general operating window shown in this diagram, the range of possible scanning speed values (usually limited only by the machine parameters) can be relatively large. However, in certain combinations with laser power, inappropriate or insufficient melting of the powder can occur, and this must be avoided or corrected using other process parameters such as hatching distance.

3 EXPERIMENT – THE EFFECT OF LAYER PRINT SPEED ON THE QUALITY OF THE LOWER SURFACE

3.1 *Description of the experiment and samples*

In order to demonstrate the effect of Layer Print Speed on the properties of printed pieces, a simple experiment was performed in which its effect on the quality of the lower inclined surface was observed. This speed has a great influence on the laser heat dissipation rate, which is manifested in many ways, such as internal stress in the printed volume. However, the quality of the lower inclined surface is very apparent, as heat dissipation through the surrounding powder is significantly worse than heat transfer through a solid material. Moreover, this method of heat transfer is limited depending on the angle of inclination of the bottom surface. As the angle increases, a larger part of this surface is in contact with the powder, which means a greater accumulation of thermal energy and consequently poorer surface quality. For this reason, support structures are recommended for lower surfaces inclined by more than 40° to 45°, which stabilize the printed piece and allow better heat dissipation to the printing platform. Nonetheless, if a Layer Print Speed is set which allows sufficient heat dissipation, it is possible to minimize the volume of these support structures. This is a great benefit as printing these structures prolongs the total Print Time, increases material consumption and removing them requires additional finishing operations. In order to verify the effect of Layer Print Speed on the quality of the lower inclined surfaces, a special experiment was prepared in which a large number of experimental samples were printed using different process parameters.

Groups of samples (see Fig. 5) with bottom surfaces inclined at angles of 35°, 40°, 45° and 50°, which were located at different printing levels, were used to observe the effect of Layer Print Speed on the quality of the lower inclined surfaces. The levels were chosen in such a way that different numbers of samples were printed in each of them, which resulted in differently sized sintered areas and thus different Layer Print Speeds.

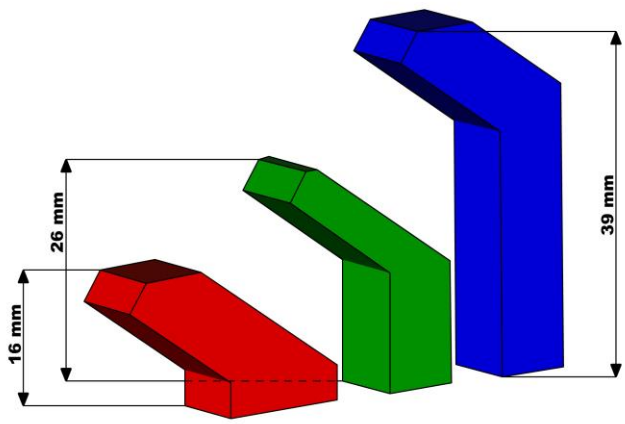

Figure 5. Types of experimental samples

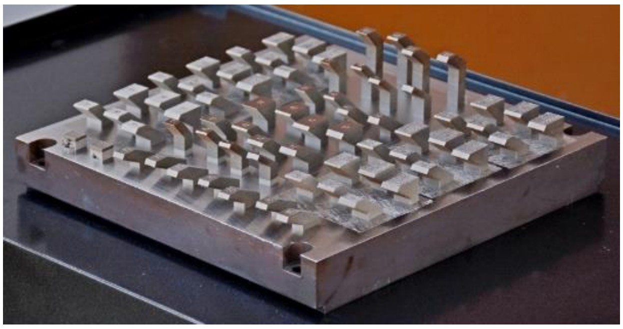

Figure 6. Printing platform with experimental samples

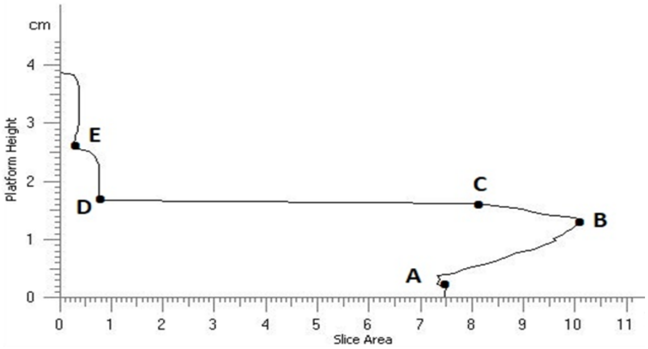

Figure 7. Mass distribution in individual layers of the print job

An EOS M 290 machine was used for the experiment. This model has a building volume of 250 x 250 x 325 mm and uses an Yb fibre laser with max. 400 W beam power, up to 7.0 m/s scan speed and 80 µm focus diameter. EOS Maraging Steel MS1 (AKA 1.2709 or X3NiCoMoTi 18-9-5) with 8000 kg/m³ density was used as the build material, and nitrogen as the protective atmosphere.

	inskin	downskin	upskin
Hatch distance [mm]	0.11	0.05	0.09
Scanning speed [mm/s]	960	2400	600
Laser power [W]	285	145	153
Beam offset [mm]	-0,055	-	-
Hatch stripe width [mm]	10	10	1000
Hatch stripe overlap [mm]	0.08	0	0
Recoater speed [mm/s]	150 (layer creating) 500 (returning)		
Platform preheating temperature [°C]	40		

Table 1. Process parameters used for the experiment

3.2 *Results and analysis of the experiment*

The experimental platform (Fig. 6) contained samples inclined at different angles and with 3 different heights. The lower samples were 16.3 mm high (samples I), the medium samples 25.56 mm (samples II), and the highest samples 38.56 mm (samples III). The experiment was designed so that some of the bottom surfaces of sample II started to be printed together with the type I samples, while all the bottom surfaces of sample III started to be printed after all the other prints had been completed. As shown in Fig. 7, the volume distribution of the whole printed volume was intentionally very uneven with this setting.

Fig. 7 shows the distribution of the printed volume in individual printing layers. The X axis represents the print height, the Y axis the printed area at a given print height. The letters indicate significant changes in the printed areas. Point A indicates the end of printing the 4 mm high support structures that all the samples had. Point B indicates the layer in which the printed area was the largest. Point C indicates the last layer in which type I samples were printed, and point D indicates the layer immediately following it. Point E indicates the end of printing Type II samples. Different printed areas correspond to different printing durations of the respective layers. Layers marked with letters are especially important for the evaluation of this experiment.

The Print Times of these layers and their corresponding speed values are listed in the following Table 2.

It can be seen from Table 2 that the Area Print Speed of the same samples at point B is significantly higher than at the following point C. This deceleration is caused by the printing of the upper layers (the upskin) of the medium-high samples, which were printed in the area of point C and for which parameters with a lower speed of laser beam movement were used. Since the calculation of the Layer Print Speed values in these individual layers is equal to the inverse value of the Print Time in seconds, this value is not given here, in contrast to the more telling values of the Print time. As confirmed by the software simulation and the video recording of the experiment, the Area Speeds could be different in each printed layer (e.g. depending on the sizes of inskin, upskin and downskin areas), and therefore the table shows the values in two consecutive layers (n and n +1). As can be seen from Table 1, the marked layers Print Times, and the subsequently calculated respective speeds, are very different, and in some cases even several times faster.

Layer Location	Print Height [mm]	Printed Area in Layer [n] [mm²]	Layer (n)		Layer (n+1)	
			Print Time [s]	**Area Print Speed** [mm²/s]	**Print Time** [s]	**Area Print Speed** [mm²/s]
Point A	**4.00**	**7491**	104	72	120	62
Point B	**13.16**	**10147**	156	65	134	76
Point C	**16.28**	**8065**	170	47	168	48
Point D	**16.32**	**768**	21	37	21	37
Point E	**25.56**	**256**	37	7	10	26

Table 2. Print times and Area Print Speeds in selected layers

These differences are easily visible on the surfaces of the printed samples, see Fig. 8, 9, 10.

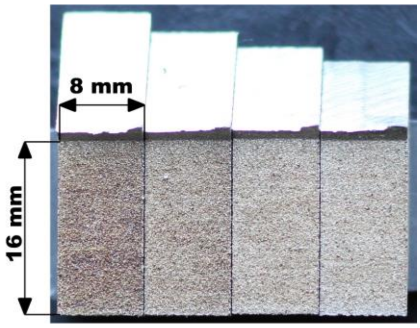

Figure 8. Samples with extended cooling time of type I sorted by angles of 35 °, 40 °, 45 ° and 50 °

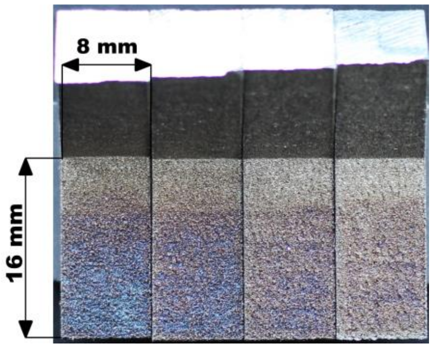

Figure 9. Samples with extended cooling time of type II sorted by angles of 35 °, 40 °, 45 ° and 50 °

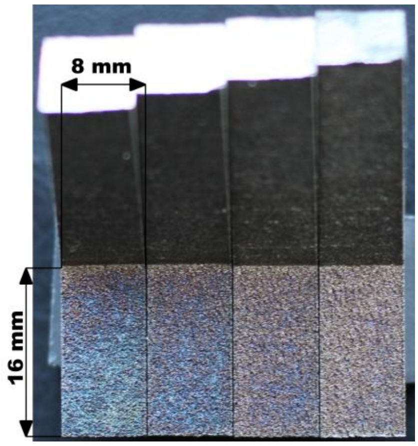

Figure 10. Samples with extended cooling time of type III sorted by angles of 35 °, 40 °, 45 ° and 50 °

From the above images, it is clear how the time/speed of layer printing affects the surface quality of virtually all the lower inclined surfaces. It is evident that all type III samples have the worst surface quality. These were printed separately and thus with the shortest individual layer Print Time. In the experiment, these individual layer Print Times were artificially extended to twice the original time by slowing down the forward and backward speeds of the recoater. However, such manipulation of the Layer Print Speed was not sufficient and therefore not effective, which corresponds to the inferior surface quality.
In contrast, the best surface qualities were obtained on the type I samples with the bottom surface printed between points A and D, and the bottom surface area on the type II samples printed between points B and D. The second part of the type II sample area, which was printed after completing the printing of the lower samples, i.e. between points D and E (marked with a black line in the picture), achieves significantly worse roughness quality Ra, Rq, and Rz in all areas. All these areas were scanned using an Alicona optical microscope which created 3D models of given surfaces and determined their detailed roughness profiles. The roughness analyses were performed according to ISO 25178 standard; twice consecutively for all areas using two straight long lines and a zig-zag line together with an Lc parameter (i.e cutoff wavelength) set to 8 mm in accordance with ISO 4288. The respective roughness values, which were obtained by the arithmetic average of the measured values with a small variance, are given in Table 3.

Individual Areas			35°	40°	45°	50°
I	A ↓ D	Ra	36	32	29	24
		Rq	44	40	37	31
		Rz	236	226	237	206
II	B ↓ D	Ra	36	32	24	21
		Rq	45	41	31	27
		Rz	243	222	183	166
	D ↓ E	Ra	53	47	41	35
		Rq	65	58	52	45
		Rz	334	327	295	257
III	E ↓	Ra	60	48	38	33
		Rq	74	59	48	41
		Rz	364	344	298	232

Table 3. Roughness of lower inclined surfaces of sample types I, II, III

As can be seen from this table, the best roughness values are achieved by type I samples and by parts of the surfaces of type II samples (Table 3 contains values for both bottom surface qualities "B-D" and "D-E"). However, the samples printed with low layer Print Times had the worst roughness values. The best values of the individual roughness categories at different angles of inclination are marked in green, the worst values in red. It is also evident from the table that some of the best values were not reached by type I samples, although they were printed at the same speed as the bottom part of type II samples. This difference was probably caused by measurement inaccuracies, as it was possible to measure a significantly smaller area of the surface roughness of the bottom area of the type II samples, and this area had the most advantageous location in terms of heat dissipation due to its proximity to the solid material stem. Overall, this table also confirms the increasing influence of the Layer Print Speed (which affects thermal energy dissipation from the laser beam into the printing platform) on the surface quality of the lower surfaces at decreasing angles of inclination.

4 CONCLUSION

The experiment showed that there is an evident relationship between the surface quality and Layer Print Speed (and thus the Print Times) for the inclined lower surfaces. As the inclination angle of these surfaces decreases, this dependence increases, as confirmed by the surface roughness values of the samples, due to the deteriorating laser beam heat dissipation from these staircase-shaped surfaces. The experiment revealed this relationship by using experimental print job which took advantage of the large number of printed samples that significantly prolonged the Print Times of certain layers.

However, for the practical use of this "speed-quality" effect, a more efficient tool is needed, which could be universally applicable for influencing the Area Print Speed, and hence the Layer Print Speed.

There are several options available. The basic way is to set up custom process parameters for a specific number of layers, especially the Scanning Speed which must, however, fit in combination with other appropriate parameters into the particular process window. Other effective options, if the print job's preparation software allows it, is Skywriting, Minimum Layer Time setting, or a special, usually predefined, scanning strategy, which enables influencing the Area Print Speed and the Layer Print Speed. In addition to these options, it is also possible to use some advanced Time or Energy Homogenization functions, which can effectively compensate for time differences in the printing of some areas or whole printing layers. In this way, problems such as overheating or short-hatching can be prevented in a targeted manner. Another method of purposeful speed reduction and homogenizing the print layer times is to use a virtual object, a so-called 'ghost part'. In both cases, these approaches prolong the total Print Time, however, at the same time, they can also improve the printed part's shape and its mechanical properties, especially by reducing internal stress. Nevertheless, this improvement has only been investigated on simple and comparatively bulky specimens, so it would be useful to conduct further research aimed at exploring more complex parts. Moreover, this possibility of energy input changes during the printing process can also affect the e.g. microstructure of the printed pieces, the internal stresses, and the resulting mechanical properties, therefore, a comprehensive investigation of their resulting material and mechanical properties is needed. In general, such testing of properties should be performed for any changes to the verified process parameters, including the aforementioned changes to the scanning strategy or the use of a powder with a different particle size distribution.

In the case of the purposeful Area or Scanning Speed changes described in this article, which can occur naturally and unintentionally during the printing process, the energy input changes are not too significant (e.g. compared to another support-free manufacturing method such as High Energy Downskin), but they can still affect the cooling dynamics of the powder bed to some extent. For this reason, microhardness (on 22 spots of each area) and phase analysis on selected cut-outs were performed on the lower surfaces of the described experimental samples. The following analyses concluded that neither of these tests revealed any significant deviation from the reference samples printed with standard parameters, the microstructures were similar and the test results obtained had a relatively large variance and didn't show any trend. Moreover, in the case of porosity, which ranged from 0.05 to 0.41%, some samples achieved even better values than the standard prints often do. Nonetheless, no conclusion can be drawn from these analyses; it would have been useful to perform, for example, a tensile, Charpy, or fatigue test, which was not well enough possible in the case of experimental samples in such a design.

In any case, the ability to influence print speeds can be very useful as it can improve or prevent disruption to the manufacturing process. To describe the entire production process and the key interrelationships, this article identifies the individual speeds present in the production process, describes the links between them and effective ways of adjusting these speeds. Influencing each of these speeds usually has its advantages and disadvantages, and therefore it is always essential to consider each case individually and in a broader context when these changes in speed are well-founded and at what level it is most efficient to do so.

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CONTACTS:

Ing. Martin Nozar, Ph.D.
University of West Bohemia, Faculty of Mechanical Engineering, Regional Technological Institute
Univerzitni 8, Plzen, 306 14, Czech Republic
+420377368726, nozar@rti.zcu.cz, www.rti.zcu.cz