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ROUGHNESS OF PLANE FACES PRODUCED BY ADDITIVE MANUFACTURING

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ABSTRACT: *Surface roughnesses of additive manufactured parts are often not comparable with cut parts. Prediction techniques are developed for surface roughness based on experimental databases. Nowadays experimental investigation on surface roughness of parts manufactured by different additive technologies are necessary. In this study surface roughness measurement results on test specimen produced by a layered additive manufacturing technology are demonstrated. Plane faces of cubic test specimen were investigated.*
KEYWORDS: *xxxx*

INTRODUCTION

Surface quality in production is highly important question. Cutting procedures, especially grinding are strong in producing accurate and smooth surfaces. However there are some problematic features of cutting technologies from the viewpoint of environmental consciousness. That's why they have to be developed or alternatives are sought.

Many kind of additive manufacturing technologies gain currency in the world today. They have the advantage of high technological flexibility, but accuracy and surface roughness of them has to be viewed with critical eyes. Maybe additive technologies represent a new paradigm: many of them are in the stage of research and development. Surface roughnesses of additive manufactured parts are often not comparable with cut parts. Prediction techniques are developed for surface roughness based on experimental databases [3]. So, nowadays experimental investigations on surface roughness of parts manufactured by different additive technologies are necessary.

An OBJET Eden 350V machine is in operation at College of Nyíregyháza, Department of Production Engineering, Additive Manufacturing Laboratory. This is an "ink jet type" additive manufacturing system, which builds models layer-by-layer from photopolymer resin. We used Objet FullCure 720 resin [1].

TEST MODELS

Three cubic test specimens with dimension 20x20x20 mm were produced by the additive manufacturing system. On the bottom side of them a special lug was formed. The lug had double purpose. First is to identify test pieces and their orientation by asymmetrically placed grooves. Second is to fix them onto the tray of a measuring machine for further experiments (Figure 1).

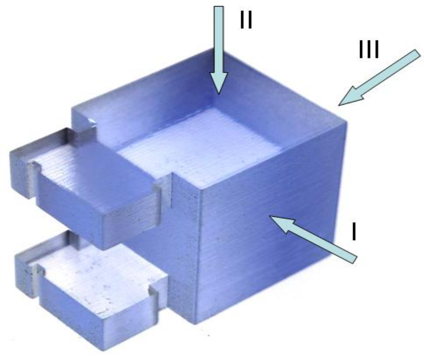

Figure 1. Test piece (id number 1) after cleaning placed as they was produced (inverted colors for better visibility)

Figure 1 shows also three orientations of faces. Direction III is the same how the printing heads move. So faces associated to orientation III are perpendicular to the movement direction of heads. Direction I is horizontal and perpendicular to III. Horizontal directions I and III lays in the plane or 16 micrometer thin layers. Direction II is vertical, this is along which the model "grows up" during the printing procedure. These notations of orientations will be used for identify measurement results.

EXPERIMENTAL METHODS

Test specimens were cleaned from the support material with 5% NaOH solution. After cleaning surface roughness of them was investigated by a Mitutoyo SJ-201P surface roughness tester. It uses a diamond stylus with tip radius of 5 micrometer, and measuring force of 4 mN.

In case of plastics there may be arguments against reliability of such a type of roughness test because of the material of tested surface is resin that is a soft and plastic material relative to the diamond tester. The question is if the measuring system modifies the object of measurement significantly or not. In our case we have to discuss how much stylus may rive up the surface. Of course this problem also arises in case of metals, because there are always peaks so small and thin that stylus deforms or breaks them down. The smaller the mechanical strength of the measured material the larger *is the impact on the surface of the surface tester. From measuring force and dimensions of the tip we can calculate that static pressure of*

$$\sigma_{static} = \frac{measuring\ force}{area\ of\ the\ tip} = \frac{0{,}004N}{(0{,}005mm)^2\pi} = 50{,}95\,MPa$$

arises when the tip is placed onto the surface. Dynamic effects during the measurement change this value of course. The tensile strength of the material of test specimen is 50-65 MPa, the flexural strength is 80-110 MPa, the elastic modulus (E) is 2000-3000 MPa according to the manufacturer's data [1]. Aboves have the consequences on our measurements that if the speed of the stylus is not too large (not too strong dynamic effects) then mechanical stresses generated in the surface peaks are just under the limit of failure. In case of very thin peaks residual deformation may occur. It is sure that elastic deformations always occur. Let us approximate the magnitude of elastic deformations with a simplified model. We consider the situation when the tip rests on a peak having the same cilindrical cross section and dimension as the tip (Figure 2 A), in this case the Hook's law is applied:

$$\sigma_{static} = \frac{\Delta h}{h}E \Rightarrow \Delta h = \frac{\sigma_{static} h}{E} \approx \frac{50MPa}{2000MPa}h = 0{,}025h.$$

By this approximation we can say that in case of a 10 micrometers high peak the pressure of the tip causes at most 0,25 micrometer decrease in height. Sidelong deformation of peaks does not cause so strong effect on measured surface roughness, because bending does not essentially influence the height of a peak. Yet we give a simple approximation for it: (see Figure 2 B) modeling the peak as a cylindrical prismatic bar with raduis r=5 micrometer and hight h=10 micrometer, fixed at its bottom end, assuming F=4 millinewton bending force at the free end, and taking into account elastic modulus (E) above, we get f=0,6 micrometer displacement of the end of the bar. (The well known $f = Fh/3IE$ formula was used, where $I = r^4\pi/2$ is the polar static moment of the circle cross section.)

After this consideration we state that our surface roughness tester can be applied for measure our test specimen made of resin. We expect that influence of measuring tool on surface roughness remains in the magnitude of 1 micrometer. This error is systematically negative, while diamond tips never increases or „builds up" peaks, but always destroys or pushes down them. Probably the roughness parameter Rz is mostly affected by this type of error (the definition is in the next chapter).

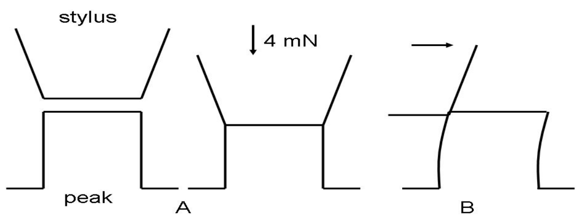

Figure 2. Simplified considerations on basic types of peak deformations

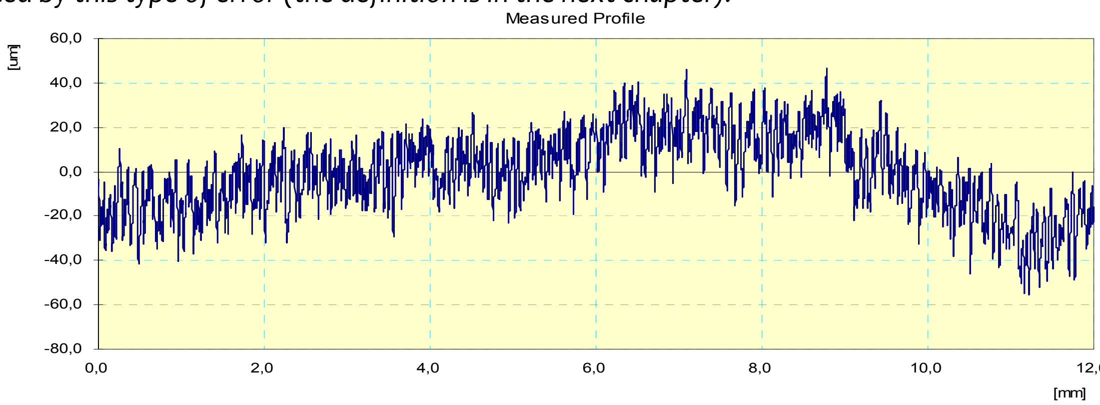

Figure 3. An example for the primary profile

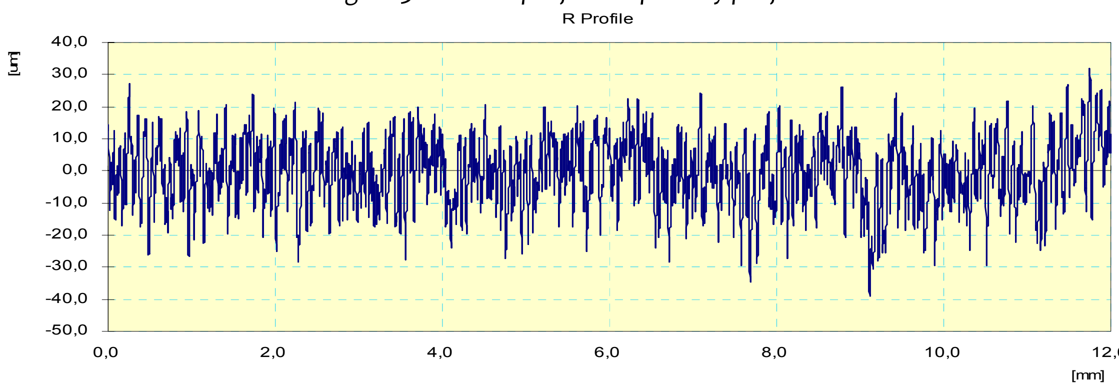

Figure 4. Filtered profile

The surface roughness tester records the so-called primary profile by differential inductance method (Figure 3.) This is an electronic signal. It involves information on surface roughness and long-range irregularities, what are not treated as roughness, indeed size errors. The long-range irregularities appear in the signal as long wavelength components, and they are filtered out in an electronic way (Figure 4.) The result depends on the type of the filter, because transmission characteristic of them are different. That's why we performed our measurements with two variant filters to see how much results differ. Both 2RC75 and PC50 are high-pass filters, but amplitude transmittance of PC50 decreases more rapidly, so it filters out even shorter wavelength components of the signal.

Table 1. Results with 2RC75 filter

Ra	orientation I.			orientation II.			orientation III.		
2RC75 filter	measuring position			measuring position			measuring position		
id number of test specimen	1	2	3	1	2	3	1	2	3
1	8,43	9,37	9,74	1,76	2,19	1,98	10,41	9,25	9,65
2	9,29	9,20	9,20	5,45	6,00	5,02	11,27	11,63	11,29
3	10,42	8,14	8,66	3,18	2,48	3,02	10,47	9,84	10,14
		mean	9,16		mean	3,45		mean	10,44
		st. dev	0,69		st. dev	1,61		st. dev	0,82

Rq	orientation I.			orientation II.			orientation III.		
2RC75 filter	measuring position			measuring position			measuring position		
id number of test specimen	1	2	3	1	2	3	1	2	3
1	10,41	11,74	12,03	2,22	2,70	2,60	12,79	11,51	11,77
2	11,61	11,47	11,35	10,96	11,20	9,86	14,20	14,31	13,87
3	14,32	10,27	10,69	5,08	3,55	3,96	13,07	12,37	12,81
		mean	11,54		mean	5,79		mean	12,97
		st. dev	1,21		st. dev	3,77		st. dev	1,01

Rz	orientation I.			orientation II.			orientation III.		
2RC75 filter	measuring position			measuring position			measuring position		
id number of test specimen	1	2	3	1	2	3	1	2	3
1	64,63	71,76	71,36	13,46	15,05	16,48	77,57	75,72	68,83
2	76,11	78,34	68,38	73,68	76,73	68,89	90,61	90,54	98,28
3	107,60	63,56	71,09	41,67	26,44	25,43	94,66	76,53	81,27
		mean	74,76		mean	39,76		mean	83,78
		st. dev	13,21		st. dev	26,45		st. dev	10,04

Table 2. Results with PC50 filter

Ra	orientation I.			orientation II.			orientation III.		
PC50 filter	measuring position			measuring position			measuring position		
id number of test specimen	1	2	3	1	2	3	1	2	3
1	8,62	9,48	9,70	2,82	2,83	2,24	10,26	9,89	10,43
2	9,16	9,27	9,08	2,70	2,45	2,56	11,63	11,85	11,10
3	9,19	8,38	8,55	1,71	2,19	1,99	9,27	9,70	9,32
		mean	9,05		mean	2,39		mean	10,38
		st. dev	0,44		st. dev	0,39		st. dev	0,96

Rq	orientation I.			orientation II.			orientation III.		
PC50 filter	measuring position			measuring position			measuring position		
id number of test specimen	1	2	3	1	2	3	1	2	3
1	10,77	11,74	11,94	3,53	3,89	3,07	12,80	12,21	12,91
2	11,26	11,45	11,20	3,34	3,12	3,22	14,27	14,55	13,63
3	11,62	10,27	10,48	2,10	2,90	2,39	11,68	11,97	11,65
		mean	11,19		mean	3,06		mean	12,85
		st. dev	0,58		st. dev	0,55		st. dev	1,09

Rz	orientation I.			orientation II.			orientation III.		
PC50 filter	measuring position			measuring position			measuring position		
id number of test specimen	1	2	3	1	2	3	1	2	3
1	67,01	78,29	65,95	22,91	26,40	20,67	80,43	78,68	80,34
2	71,61	68,90	72,75	21,49	20,05	21,02	81,53	85,78	73,98
3	81,00	60,84	59,92	11,49	20,46	13,96	74,87	66,14	78,81
		mean	69,59		mean	19,83		mean	77,84
		st. dev	7,16		st. dev	4,50		st. dev	5,61

RESULTS

The surface roughness tester automatically analyzed the profiles, and calculated the following surface roughness parameters.

Arithmetic mean deviation of the profile (Ra): $Ra = \frac{1}{N}\sum_{i=1}^{N}|Y_i|$,

where: N means the number of sampling points along the sampling length (now 1000), Y the deviation from the mean line at the certain sample point.

Root-mean-square deviation of the profile (Rq): $Rq = \sqrt{\frac{1}{N}\sum_{i=1}^{N}Y_i^2}$.

Maximum height of the profile (Rz): $Rz = \frac{1}{n}\sum_{i=1}^{n}Z_i$, $Z_i = P_i + V_i$,

where: P_i and V_i stands for the highest peaks and the deepest valley within a sampling length, so Z_i is the width of the profile, n is the number of sampling length in the evaluation length.

Results are in agreement with what we expect by our senses and by knowledge on the technology. Faces perpendicular to the direction II, that is horizontal when the test specimen is printed, are the smoothest. These faces are parallel with layers finished by a cylinder under building up. Faces in the other two directions (vertical when printed) show substantially larger roughness.

EVALUATION OF RESULTS

Before statistical analysis it is worth to perform an F-test to decide if samples can come from population with the same variance or not. If yes, we can use simpler statistical tests. In our case it is very simple. We investigate values of standard deviation belong the same roughness parameter and the same filter. We choose significance level of 0.05. The test statistics is $F = s_1^2 / s_2^2$, we calculate it always so that it be greater than 1. Both of degrees of freedom are 3-1=2, so the critical value is $F_{0,05}(2,2) = 19,0$. Calculating all fractions, we can see that none of them is greater than 19. This means that for a certain roughness parameter and filter each sample can be supposed to come from populations with the same variance at significance level α=0.05.

For comparison of mean values we apply two sample z-test. The test statistics is

$$z = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}},$$

where $\overline{x}_1$ and $\overline{x}_2$ are mean values, s_1 and s_2 are variances of populations approximated by standard deviations of samples, n_1 and n_2 are number of samples (now always 3).

The null hypothesis is that mean value of the two population are equal, and it is accepted true at the chosen significance level if $|z|<1.96$. After evaluating the test statistics one can see that many of them are greater than 1.96 (Table 3).

Table 3. Two sample z-test values

2RC75 filter	z
Ra I. - II.	5,64
Ra I. - III.	-2,07
Ra II. - III.	6,70
Rq I. - II.	2,51
Rq I. - III.	-1,57
Rq II. - III.	3,18
Rz I. - II.	2,05
Rz I. - III.	-0,94
Rz II. - III.	2,69
PC50 filter	**z**
Ra I. - II.	19,62
Ra I. - III.	-2,19
Ra II. - III.	13,43
Rq I. - II.	17,70
Rq I. - III.	-2,33
Rq II. - III.	13,89
Rz I. - II.	10,19
Rz I. - III.	-1,57
Rz II. - III.	13,97

CONCLUSIONS

Surface roughness of cubic test specimen produced by layer-by-layer additive manufacturing technology was studied. Standard deviations of roughness values are not statistically different. Mean values shows significant difference at significance level 0.05. Faces in direction II are far smoother than other faces.

We note that roughness of faces in orientation I and III are close to each other, Ra of them are significantly different, Rz is not, Rq is significantly different only if measured with PC50 filter.

Surface roughness of faces in directions I and III are comparable usual roughness parameters of milled and turned surfaces. Roughness of faces in direction II is close to roughness of grinded metal surfaces.

REFERENCES

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[3.] Daekeon Ahn, Hochan Kim, Sheokhee Lee: Surface roughness prediction using measured data and interpolation in layered manufacturing, Journal of Materials Processing Technology, 209 (2009) 664-671